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The Hazard of Exposure to Impulse Noise as a Function of Frequency

Volume I

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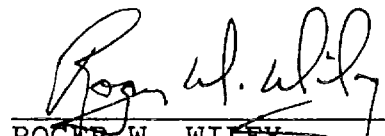

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The energy spectrum of a noise is known to be an important variable in determining the effects of a traumatic exposure. However, existing criteria for exposure to impulse noise do not consider the frequency spectrum of an impulse as a variable in the evaluation of the hazards to the auditory system. This report presents the results of a study that was designed to determine the relative potential that impulsive energy concentrated at different frequencies has in causing auditory system trauma. One hundred and eighteen (118) chinchilla, divided into 20 groups with 5 to 7 animals per group, were used in these experiments. Pre- and post-exposure hearing thresholds were measured at 10 test frequencies between 0.125 and 8 kHz on each animal using avoidance conditioning procedures. Quantitative histology (cochleograms) was used to determine the extent and pattern of the sensory cell damage. The noise exposure stimuli consisted of six different computer-generated narrow band tone bursts having center frequencies located at 0.260, 0.775, 1.025, 1.350, 2.450, and 3.550 kHz. Each narrow band exposure stimulus was presented at two to four different intensities. An analysis of the audiometric and histological data allowed a frequency weighting function to be derived.

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The weighting function clearly demonstrates that equivalent amounts of impulsive energy concentrated at different frequencies is not equally hazardous to auditory function. Comparison of this weighting function with the A-weighting function showed that A-weighting overestimates the hazard from low frequency impulses. Volume 1 of the report describes the study and discusses the results. Volume 2 contains individual threshold shifts and sensory cell loss data. It is available upon request from the SIC USAARL.

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Introduction

It has long been recognized that exposures to steady noise at different frequencies were not equally hazardous. The National Academy of Sciences Committee on Hearing, Bioacoustics and Biomechanics (CHABA) damage risk criteria for steady noise provided weighting functions which represented the relative hazard associated with noise exposures of different spectral content (Kryter et al., 1966). More recently, these weighting curves have been simplified to the A-weighting function which has been incorporated into many sound level meters. To a first approximation, A-weighting of steady noise provides a good estimate of the relative hazard to hearing of the various frequencies which comprise a steady noise exposure (Mills et al., 1983).

In contrast, the early damage risk criteria for impulse noise [e.g., Coles et al., (1968); OSHA Department of Labor, (1974); Smoorenburg, (1982); Pfander et al., (1980)] used no spectral weighting functions. For example, the Coles et al., (1968) suggestions which were incorporated into the CHABA (1968) document were formulated in terms of peak pressure and two measures of duration. The two measures of duration, the A-duration and the B-duration, resolve in practice to a limit based on only B-duration for most real world impulses. Such a criterion totally ignores any differences in the distribution of energy across frequencies. On purely theoretical grounds, this neglect of the spectrum does not seem reasonable. The auditory system transfers a pressure wave in air to fluid-borne stimulation of the auditory receptors with an efficiency which varies as a function of frequency.

Data have been reported by Price et al. (1988) showing that impulses from large bore versus small bore weapons produce a threshold of injury in cats at different peak pressures. Large bore weapons have most of their energy at low frequencies, while small bore weapons have their spectral peaks at a higher frequencies. Those results have been interpreted as indicating that a frequency selective mechanism has a strong influence over the injury resulting from exposure to impulse noise. In an earlier study, Price (1979) used tone pips to show as the energy in an impulse shifted to very high frequencies, with pressure held constant, the injuries resulting from exposure were less severe when the higher frequency tone pips were used. However, this study did not explore pulses with energy at center frequencies below 1.0 kHz.

No systematic study of injury from low frequency impulses has been reported. The objective of this study was to explore the hearing loss and cochlear injury produced by narrow band impulses with energy concentrated in the low to mid frequencies, i.e., from approximately 0.2 to 4.0 kHz.

Methods and procedures

A detailed presentation of all the methods that were used in these experiments can be found in Patterson et al., (1986). Only brief highlights of the procedures are presented below.

a. Subjects:

The subjects were 118 male chinchilla villadera. The animals were made monaural by surgical destruction of the left cochlea under halothane anesthesia, (Miller, 1970) and were allowed to recover for 2 weeks before any further experimentation took place.

b. Procedures:

Behavioral audiometry was performed using a shock avoidance procedure (Burdick, et al., 1978). A baseline audiogram was established as the average of the last five audiograms prior to exposure. The audiometric test frequencies used were: 0.125, 0.250, 0.5, 1.0, 1.4, 2.0, 2.8, 4.0, 5.7, and 8.0 kHz. Postexposure audiograms were obtained at 2 minutes, 1 hour, 3, 6, 24, 48, and 72 hours after exposure and then twice weekly until 30 days postexposure. Three audiograms were obtained during the final postexposure week. At 30 days postexposure, the animals were anesthetized and killed by decapitation. The cochleas were removed and fixed with a 2.5 percent buffered glutaraldehyde. The fixed tissue was evaluated for loss of sensory cells using surface preparation histological techniques.

c. Exposure Stimuli:

The narrow band impulse noise was produced by exciting an Altec model 515B speaker* in a model 815 enclosure with a signal produced by the PDP 11/34 computer system*. The computer synthesized signal was obtained by exciting a digital band pass filter of the 4-pole Learner-type (Gold and Rader, 1969) with a digital impulse. This filter has a bandwidth of approximately 400 Hz independent of center frequency and steep attenuation

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* See Appendix A.

outside the pass band. This permitted the synthesis of a set of impulses of equivalent energy at a variety of center frequencies while assuring minimal spread of energy to other frequencies.

The center frequencies were selected to explore the range from 0.200 to 4.000 kHz. The general strategy was to vary the energy levels of impulses at each center frequency to span the range of injury from large permanent hearing loss to little or no hearing loss. At the lowest frequency, equipment limitations prevented the synthesis of impulses intense enough to produce large permanent threshold shifts. Center frequencies, peak pressures, and sound exposure levels for each experimental group are shown in Table 1. Sound exposure levels (SEL) (Young, 1970) were computed from:

$$SEL = 10 \log_{10} \int_{\infty}^{\infty} (P^2(t)/P_r^2 t_r)\, dt$$

where t_r = 1s and P_r = 20 μPa.

Table 1

Definition of experimental groups.

Group	N	Center frequency (Hz)	Peak SPL (dB)	Total SEL (dB)
1	6	260	139	132.5
2	6	260	146	139.8
3	5	775	134	124.8
4	6	775	139	129.4
5	6	775	144	134.8
6	6	1025	129	119.8
7	6	1025	134	124.2
8	5	1025	139	129.1
9	6	1025	144	134.6
10	6	1350	129	119.8
11	6	1350	134	124.2
12	6	1350	139	129.0
13	6	2450	129	120.6
14	6	2450	134	124.9
15	7	2450	139	129.6
16	5	2450	144	135.0
17	6	3550	124	113.0
18	6	3550	129	119.9
19	6	3550	134	124.2
20	6	3550	139	129.5
Total	118			

Figures 1 through 6 show the impulse pressure-time histories and relative frequency amplitude spectra for the six center frequencies used. Each subject was exposed to 100 impulses at a fixed intensity and center frequency (Table 1). Five to seven subjects were exposed individually to one combination of intensity and center frequency. The impulses were delivered at a rate of one every 3 seconds. All exposures were delivered to the unprotected right ear at a normal angle of incidence.

Results and discussion

Audiometric results:

The mean preexposure thresholds for all 118 animals are reported in Table 2 along with the data of Miller (1970) and are shown plotted as a function of frequency in Figure 7. There is a good agreement between the two audiograms. The mean preexposure thresholds for each group and at each audiometric test frequency is presented in Table 3. A two-way analysis of variance with repeated measures on one factor (frequency) showed that there were no statistically significant differences in the mean preexposure thresholds among groups.

Table 2

Summary of mean preexposure thresholds (dB) for all animals (N = 118) compared to published norms.

	Test frequency (Hz)										
	125	250	500	1000	1400	2000	2800	4000	5700	8000	
Present study	23.6	7.8	2.4	1.7	1.7	1.4	2.0	2.0	2.7	4.4	$\bar{x}$
	2.2	3.8	4.4	3.7	4.1	3.9	3.7	3.2	2.8	3.7	s
Miller (1970)	19.9	8.8	5.1	3.0	2.2	2.7	-0.2	1.9	1.9	5.8	$\bar{x}$
	5.4	3.9	6.1	4.1	6.6	4.7	4.9	7.1	6.7	5.4	s
	36	36	36	36	34	36	35	36	35	36	N

Table 3

Preexposure threshold means (dB) and standard deviations for all groups.

		Test frequency (Hz)										
Group	N	125	250	500	1000	1400	2000	2800	4000	5700	8000	
1	6	24.83	10.33	2.00	1.50	1.83	3.17	3.17	2.50	2.50	3.83	$\bar{X}$
		1.17	0.82	2.97	2.07	2.48	1.72	1.72	1.64	2.43	1.72	s
2	6	23.17	5.50	2.17	1.17	1.17	-0.17	1.83	1.50	1.50	3.17	$\bar{X}$
		1.72	2.07	3.06	2.79	2.32	1.72	1.17	2.59	1.05	1.72	s
3	5	23.20	6.40	1.20	3.20	1.00	1.00	0.40	0.60	2.40	6.20	$\bar{X}$
		2.17	3.05	2.77	1.30	3.54	1.87	1.82	1.52	0.55	4.32	s
4	6	25.00	10.67	3.00	0.67	1.67	3.00	2.33	2.33	3.17	5.83	$\bar{X}$
		1.67	0.52	2.28	1.37	2.50	1.41	1.37	1.21	0.98	1.94	s
5	6	22.50	7.33	2.17	1.83	1.17	0.17	1.50	-0.17	3.17	3.67	$\bar{X}$
		1.52	2.34	2.71	1.60	2.40	1.33	1.76	0.98	2.71	1.97	s
6	6	21.17	5.33	1.17	1.83	0.17	0.83	1.17	0.83	1.17	5.50	$\bar{X}$
		3.54	1.97	2.64	2.14	1.47	1.72	3.19	1.72	1.17	2.07	s
7	6	23.17	5.17	2.17	0.83	2.50	-1.17	0.50	1.17	2.17	3.17	$\bar{X}$
		0.98	2.04	3.25	1.60	1.76	4.92	2.66	2.40	1.33	1.60	s
8	5	24.20	9.80	3.00	1.40	2.20	4.60	2.40	3.40	2.00	3.80	$\bar{X}$
		2.59	1.79	2.55	2.97	0.84	1.67	2.61	1.67	1.22	1.79	s
9	6	24.50	10.83	6.00	5.33	4.00	5.17	7.67	4.33	6.17	10.33	$\bar{X}$
		1.64	10.19	16.01	14.19	16.32	14.41	13.50	11.13	8.47	10.76	s
10	6	23.67	8.50	2.67	3.17	2.33	0.83	2.50	2.50	2.00	3.17	$\bar{X}$
		2.16	1.76	4.03	2.56	1.97	3.60	0.84	2.51	2.61	2.04	s
11	6	23.67	6.00	3.33	2.00	3.33	1.00	2.33	2.67	2.67	2.17	$\bar{X}$
		1.51	3.52	2.94	1.67	1.37	2.28	1.75	2.58	1.21	2.64	s
12	6	24.50	10.50	2.17	2.00	0.50	2.83	2.00	2.50	1.50	5.33	$\bar{X}$
		1.64	1.76	3.66	1.41	2.26	0.98	0.89	1.76	2.59	2.07	s
13	6	23.67	8.33	2.17	2.67	0.33	1.00	1.67	1.00	3.00	5.33	$\bar{X}$
		2.94	3.61	2.56	2.16	2.34	1.67	0.82	1.41	3.22	2.58	s
14	6	24.00	6.33	2.33	1.33	1.67	0.67	0.17	4.00	4.67	1.67	$\bar{X}$
		0.63	4.18	3.44	3.61	3.27	1.97	2.04	2.28	2.42	2.58	s
15	7	24.86	7.43	3.00	1.57	3.14	2.71	3.57	2.43	3.57	3.00	$\bar{X}$
		2.41	4.16	3.83	1.13	1.95	1.38	0.79	1.90	1.51	1.63	s
16	5	22.80	8.60	1.40	-0.20	1.60	-0.40	0.40	0.00	1.80	4.40	$\bar{X}$
		2.59	3.21	2.88	2.17	1.82	1.52	1.82	2.12	1.30	3.05	s
17	6	22.67	6.33	2.00	0.00	0.67	1.67	-0.67	1.00	2.00	3.83	$\bar{X}$
		2.25	1.86	2.76	2.45	2.25	1.51	3.27	1.09	2.28	2.99	s
18	6	23.67	8.00	1.33	0.83	1.00	0.33	1.00	0.67	1.67	5.33	$\bar{X}$
		3.01	4.00	2.58	1.17	3.46	1.86	1.79	1.51	1.75	2.34	s
19	6	23.00	7.33	2.00	2.00	2.67	-0.67	2.33	2.33	3.67	3.67	$\bar{X}$
		1.26	3.72	2.97	0.89	1.97	2.66	2.73	3.27	3.67	2.25	s
20	6	22.83	7.83	2.83	1.33	0.83	1.50	2.17	3.17	2.83	4.83	$\bar{X}$
		2.79	4.17	1.72	2.42	1.94	1.87	2.14	2.14	2.79	5.11	s

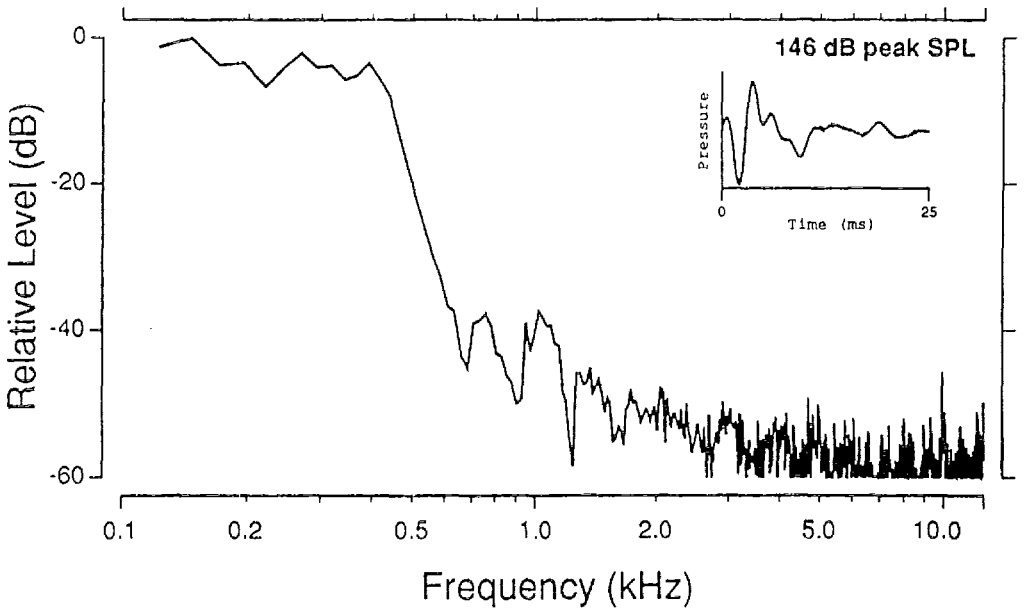

Figure 1. The narrow band impulse pressure-time waveform (inset) and the relative frequency spectrum of the impulse for the 0.260 kHz CF, 146 dB peak SPL stimulus.

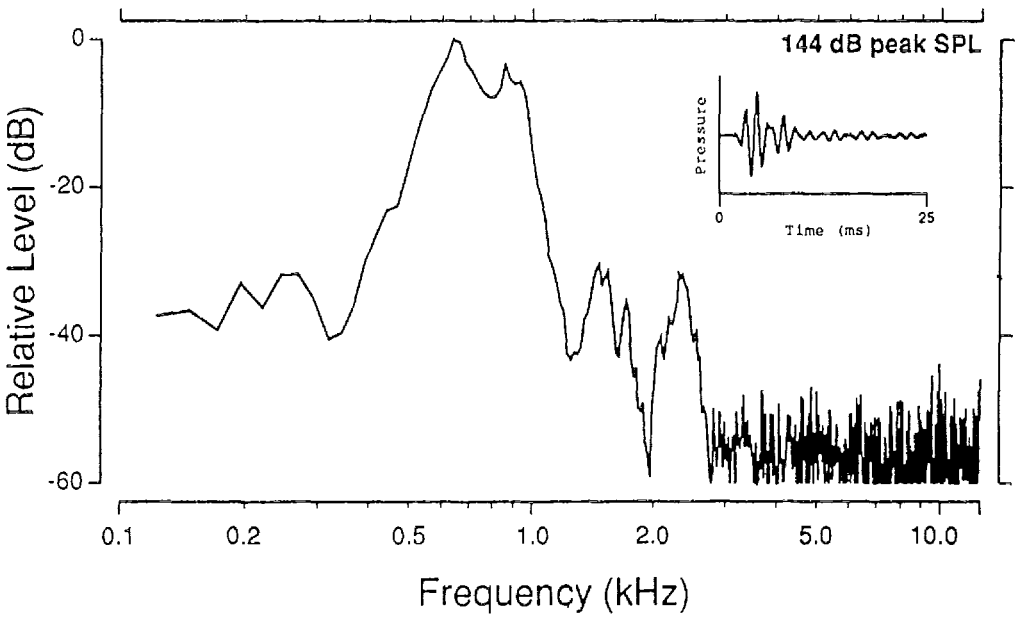

Figure 2. The narrow band impulse pressure-time waveform (inset) and the relative frequency spectrum of the impulse for the 0.775 kHz CF, 144 dB peak SPL stimulus.

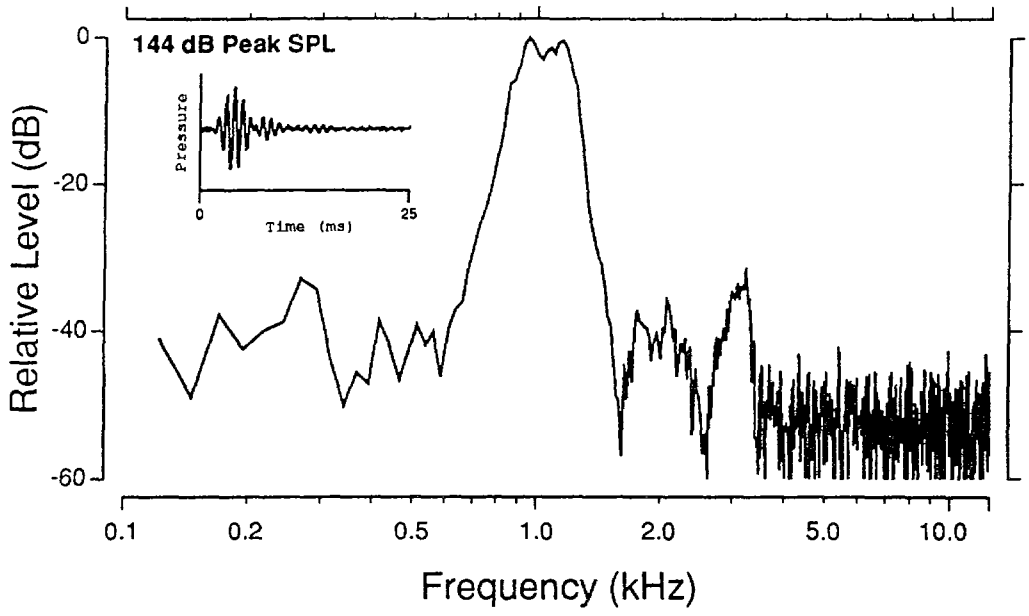

Figure 3. The narrow band impulse pressure-time waveform (inset) and the relative frequency spectrum of the impulse for the 1.025 kHz CF, 139 dB peak SPL stimulus.

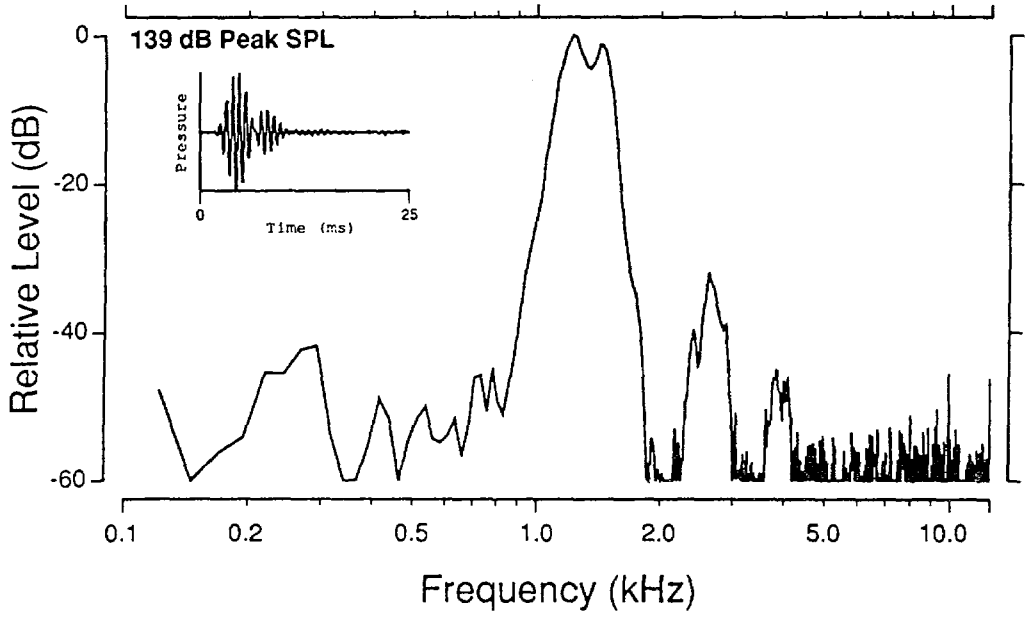

Figure 4. The narrow band impulse pressure-time waveform (inset) and the relative frequency spectrum of the impulse for the 1.350 kHz CF, 139 dB peak SPL stimulus.

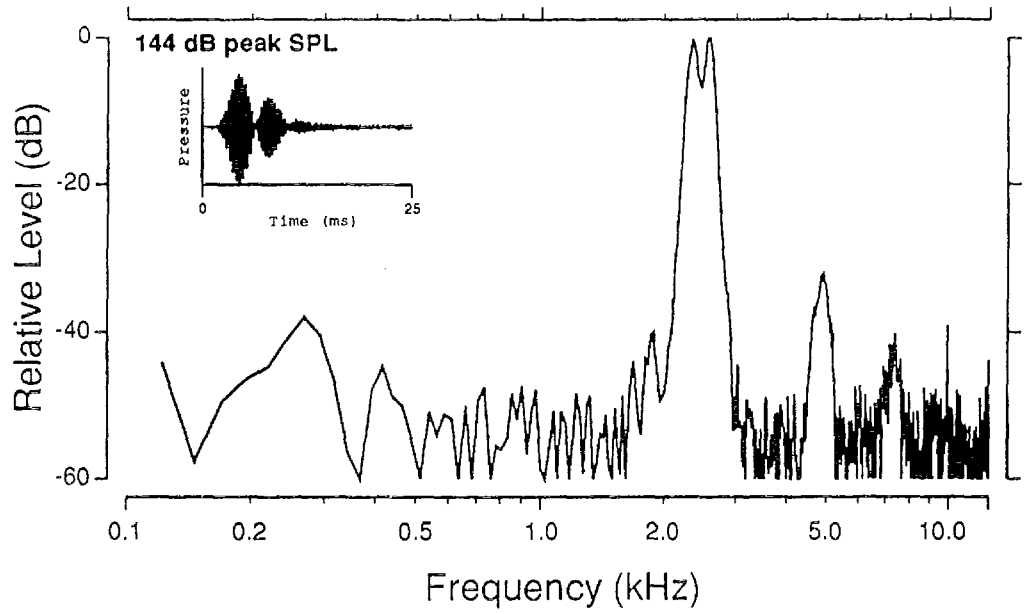

Figure 5. The narrow band impulse pressure-time waveform (inset) and the relative frequency spectrum of the impulse for the 2.450 kHz CF, 144 dB peak SPL stimulus.

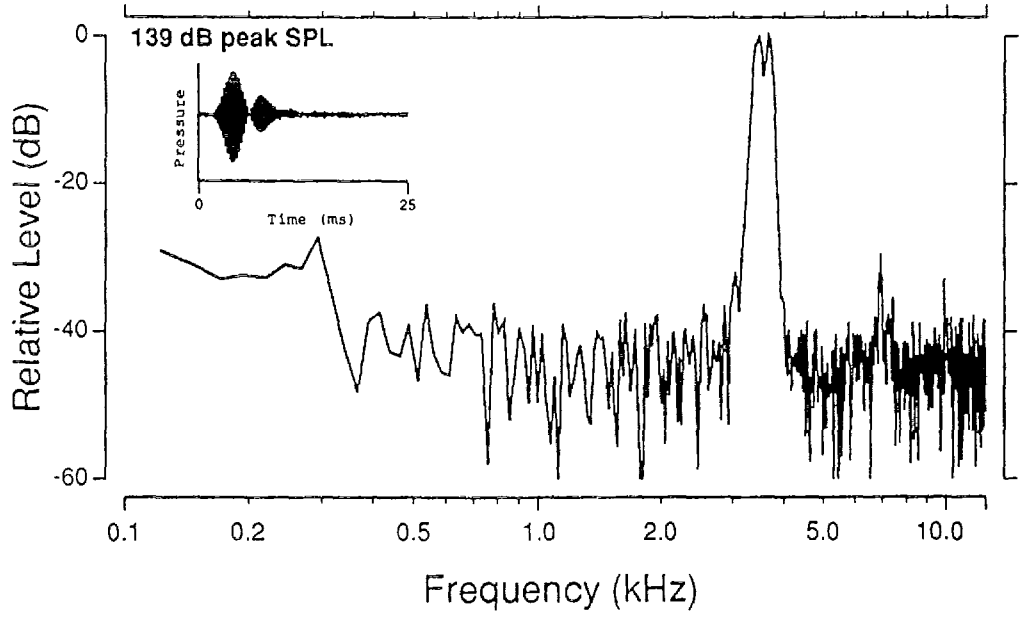

Figure 6. The narrow band impulse pressure-time waveform (inset) and the relative frequency spectrum of the impulse for the 3.550 kHz CF, 139 dB peak SPL stimulus.

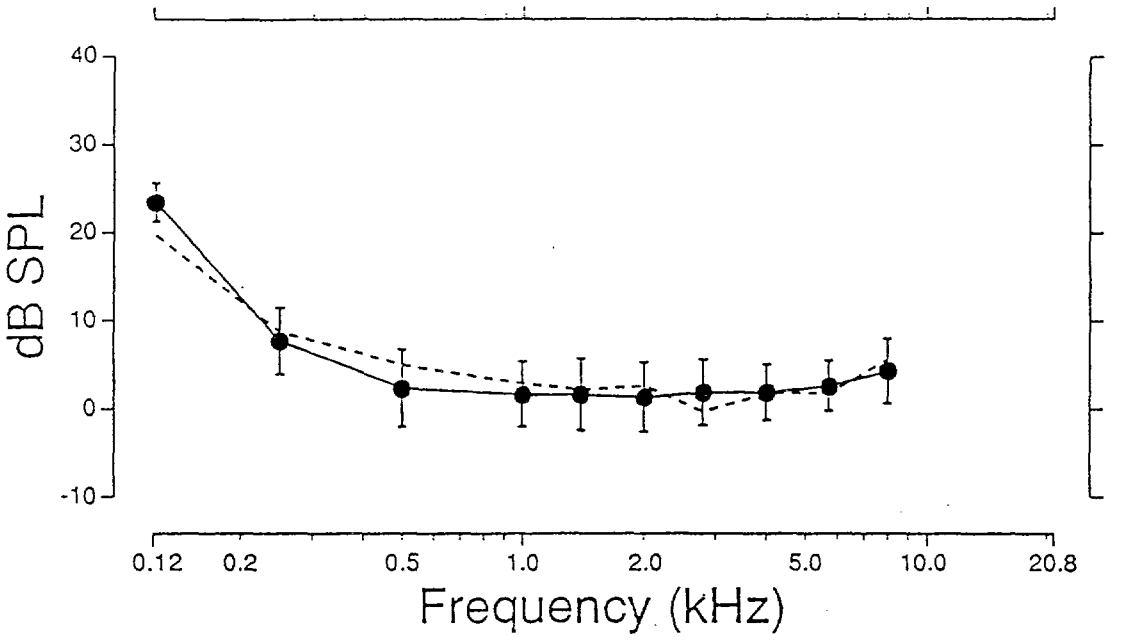

Figure 7. The mean preexposure audiogram for all 118 chinchillas (symbols) and for published norms (dashed line). The error bars represent one standard deviation above and below the plotted point.

Figures 8 through 67 illustrate the group mean threshold shifts (TS) measured over a period of 30 days postexposure (threshold recovery functions) for each of the 20 groups of animals in this study, and at each of the 10 audiometric test frequencies. In general for each noise stimulus there is an orderly relation between threshold shift and the peak SPL. Many of these recovery curves, especially those from groups exposed to the higher level stimuli, show a pronounced growth of TS or a lengthy delayed recovery, both of which have been shown to be indications of permanent changes (Hamernik et al., 1988). Because of the growth of the TS recovery functions, the first postexposure threshold measurement often is not the most appropriate index of the severity of early postexposure noise trauma. In Figures 68 through 73 the group mean maximum threshold shift (TS_{max}) for each exposure condition is shown plotted as a function of audiometric test frequency. As might be anticipated from the recovery functions, the TS_{max} shows an orderly relation with stimulus intensity for each of the stimulus center frequencies that were used. One surprising feature seen in the TS_{max} data is the lack of a clear effect of stimulus center frequency. For the noise impulses having CFs at and below 2.450 kHz, the TS_{max} audiograms are surprisingly flat between about 0.250 and 8 kHz. Only the 3.550 kHz CF stimulus produced a clear high frequency effect in the TS_{max} audiogram.

The permanent threshold shift (PTS) was computed for each animal by calculating the mean of the last five postexposure audiograms and subtracting from this the preexposure audiogram for that animal. The group mean PTS audiograms for each exposure stimulus center frequency are shown in Figures 74 through 79. The shape and ordering of these audiograms across stimulus intensity and audiometric test frequency is basically the same as that described for the TS_{max} audiograms. At the lowest CF used (0.260 Hz), the maximum exposure that was possible with the speaker used was not of sufficient intensity to produce more than a 10 dB PTS and this was confined to the test frequencies below 0.5 kHz.

Histological results

Surface preparation histology was obtained for each animal in this study, and cochleograms were plotted. Individual animal cochleograms and group cell loss data are presented in graphical and tabular form in the appendix to this report. In order to analyze the sensory cell data, inner and outer hair cell losses (IHC and OHC) were computed over lengths of the basilar membrane corresponding to octaves with center frequencies from 0.250 to 16.8 kHz, and group mean losses were computed for each exposure group. The results of this type of an analysis for each group is shown in Figures 80 through 85. As in the audiometric results, there was a general ordering of sensory cell loss as a function of stimulus intensity. This effect is evident especially in the OHC data. The inner hair cell losses show some deviation from this ordering at a few locations of the cochlea (e.g., Figure 83). A few other similar anomalies in the IHC losses, such as those evident in Figure 84, are not statistically significant.

In order to understand the relation between the audiometric data, histological data, and the stimulus variables of center frequency and intensity, the data were analyzed as follows: For each of the 20 groups of animals that were exposed to the narrow band impulses, a mean permanent threshold shift evaluated at 1, 2, and 4 kHz ($(PTS)_{1,2,4}$) was computed and the groups were compared on the basis of sound exposure level. The results of this data reduction are shown plotted as a function of SEL in Figure 86. The group mean PTS from each set of the two to four groups of animals that comprise an intensity series for a specific CF impulse behaves in an orderly manner with $(PTS)_{1,2,4}$ increasing in an approximately linear fashion with increasing SEL.

The relative susceptibility to a noise-induced PTS (NIPTS) is seen to be a function of the impulse center frequency, with the lower frequency impulses producing relatively little NIPTS even at the higher SELs. A relative frequency weighting function can be derived from the data presented in Figure 86 by shifting each center frequency intensity series data set along

the SEL axis the amount that is necessary to collapse the data into a single PTS versus SEL function using one of the exposures as a "zero" reference. Such a data shifting process was carried out "by eye" to produce a best fit using the 1.350 kHz series of data as the reference point. The amounts shifted were: 0.260 kHz CF impulses, -20 dB; 0.775 kHz CF impulses, -7.2 dB; 1.025 kHz CF impulses, -4 dB; 1.350 kHz CF impulses, 0 dB; 2.450 kHz CF impulses, -4 dB; and 3.550 kHz CF impulses, +4 dB. The realignment of the data that such a shift produces is shown in Figure 87, and the weighting function, thus obtained, is shown plotted (solid line with symbols) in Figure 88 where it is compared to the conventional A-weighting function (solid line). The new empirical weighting function is referred to as P-weighting in the text that follows. A linear regression through the shifted data set shown in Figure 87 showed a correlation coefficient of 0.894 with a slope of 2.6 dB dB PTS/dB SEL P-weighted sound exposure level. The empirical function derived from the narrow band impulse data is seen to differ from the A-weighting function by as much as 10 dB at the low frequencies. Also evident in this figure is the anomalous behavior of the data point produced by the exposures to the 2.450 kHz, CF impulses.

The histological data were reduced in a similar manner. For each of the 20 exposure conditions, the total IHC and OHC loss in each cochlea was determined and a group average total OHC and IHC loss computed. The group mean total OHC and IHC losses are shown plotted in Figure 89. As with the $(PTS)_{1,2,4}$ data shown in Figure 86, there is an orderly and approximately linear increase of cell loss with increasing stimulus intensity for each center frequency impulse. Also evident from this figure is that for a given impulse intensity, the amount of cell loss is related to the center frequency of the narrow band impulse. The effect of applying the P-weighting function derived from the audiometric data to the data in Figure 89 is shown in Figure 90. The slope of the regression line through the shifted data is 264.3 dB PTS/dB SEL and the correlation coefficient is 0.858 for total OHC loss and 12.4 dB PTS/dB SEL and 0.849 for total IHC loss.

Conclusions

Exposure to narrow band impulses whose primary energy is centered at low frequencies is much less hazardous to the auditory system than impulses with energy concentrated in the mid range frequencies. This implies that the estimation of the hazard to the auditory system from exposure to impulse noise requires a weighting function which de-emphasizes the low frequencies. A-weighting, which is commonly used in the assessment of hazard from steady noise, does not de-emphasize the low frequencies enough. Thus, A-weighted SEL will tend to overestimate the hazard from impulses with large amounts of low

frequency energy. The results of this study suggest a function more like the P-weighting function will more accurately assess the hazard from low frequency impulse noise.

There are some caveats for the conclusions drawn above. While a considerable amount of data (20 exposure conditions) were used to derive the P-weighting function, its generality can not be confirmed until it is tested with a wide variety of impulse noise exposures. In addition, it should be noted that this function was derived from chinchilla data. Data from human exposures will be required before any such function can be used for human hazard assessment.

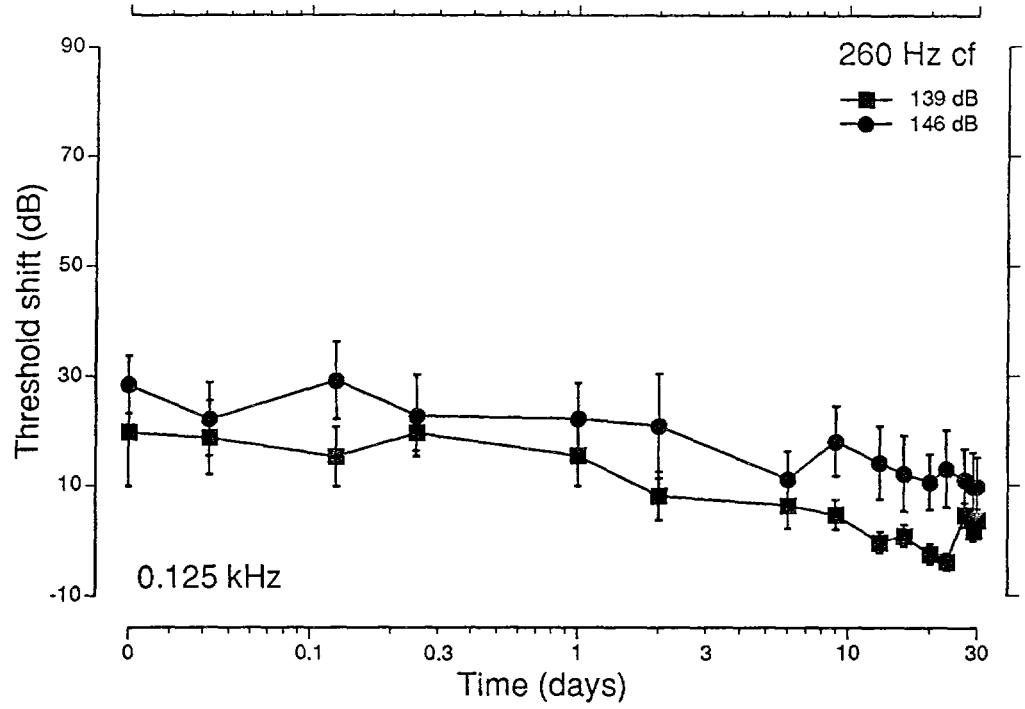

Figure 8. The mean threshold recovery curves for the groups exposed to the 0.260 kHz CF impulse at the indicated peak SPL for the 0.125 kHz audiometric test frequency.

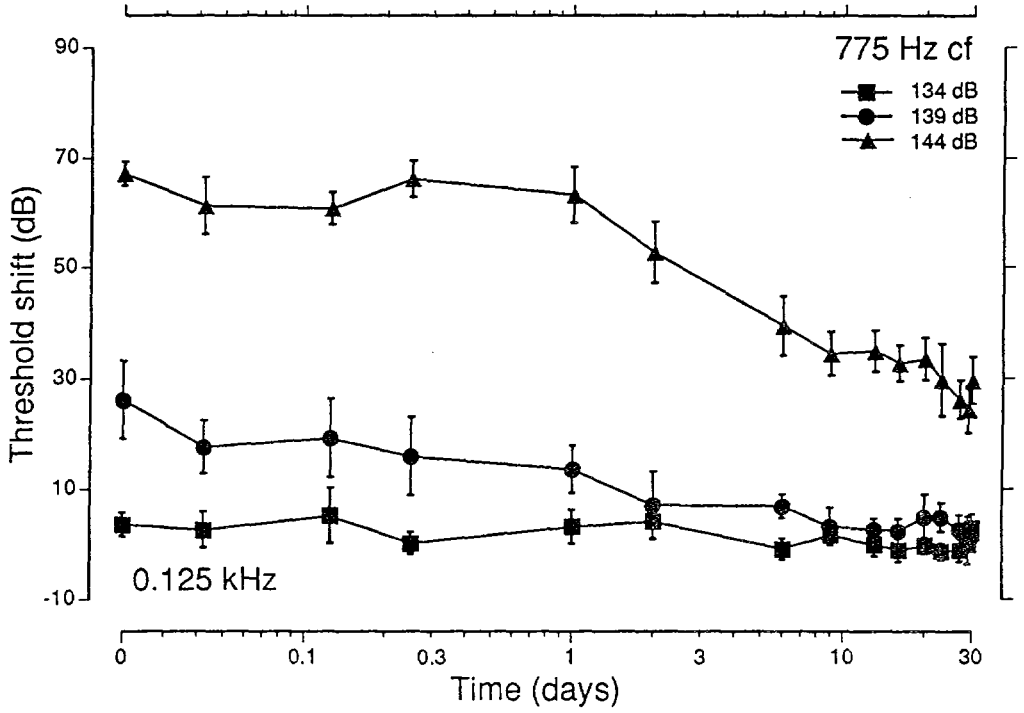

Figure 9. The mean threshold recovery curves for the groups exposed to the 0.775 kHz CF impulse at the indicated peak SPL for the 0.125 kHz audiometric test frequency.

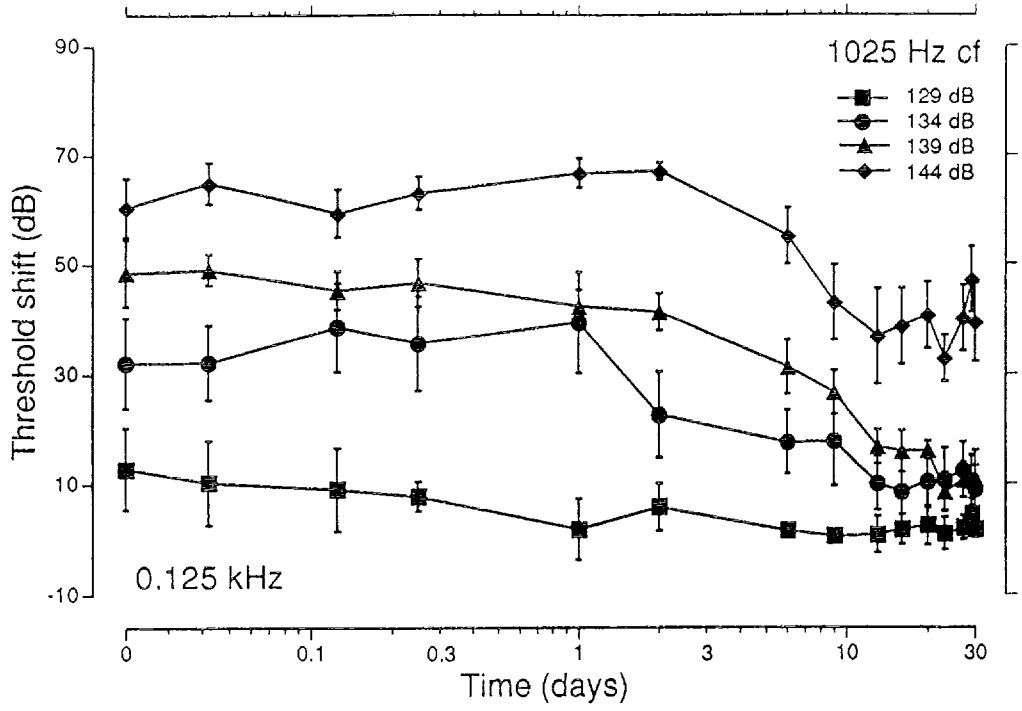

Figure 10. The mean threshold recovery curves for the groups exposed to the 1.025 kHz CF impulse at the indicated peak SPL for the 0.125 kHz audiometric test frequency.

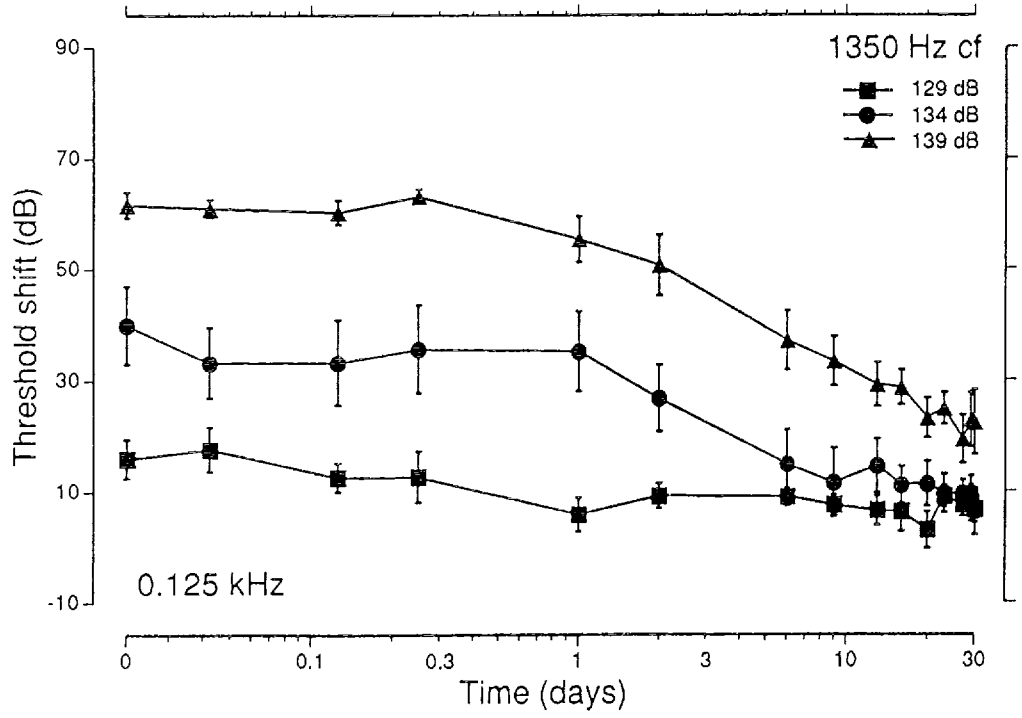

Figure 11. The mean threshold recovery curves for the groups exposed to the 1.350 kHz CF impulse at the indicated peak SPL for the 0.125 kHz audiometric test frequency.

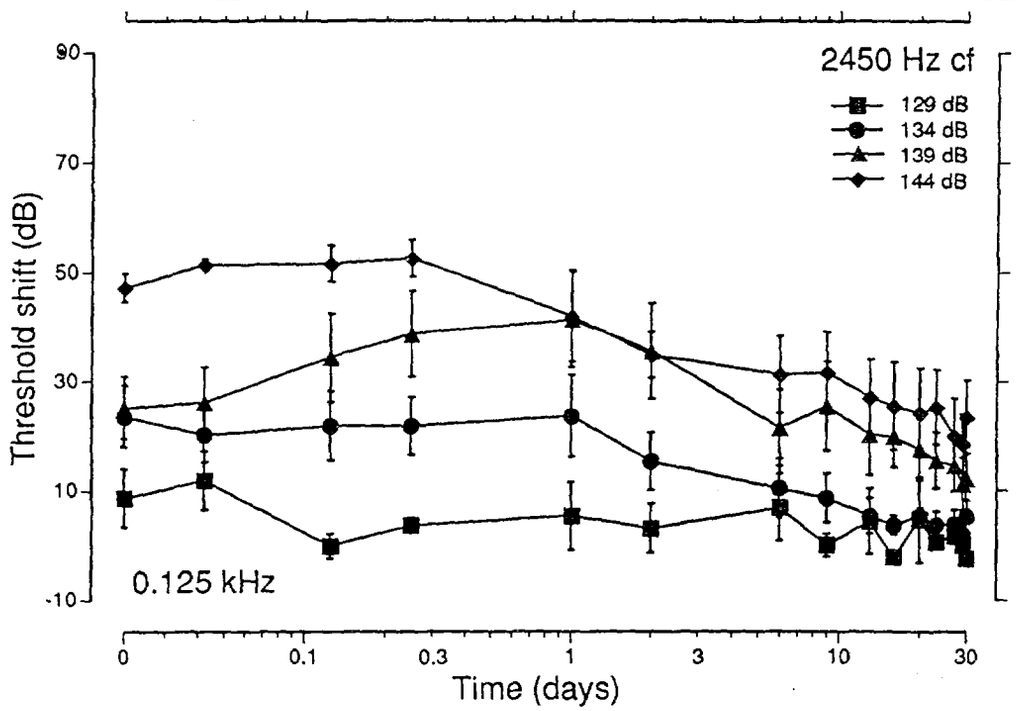

Figure 12. The mean threshold recovery curves for the groups exposed to the 2.450 kHz CF impulse at the indicated peak SPL for the 0.125 kHz audiometric test frequency.

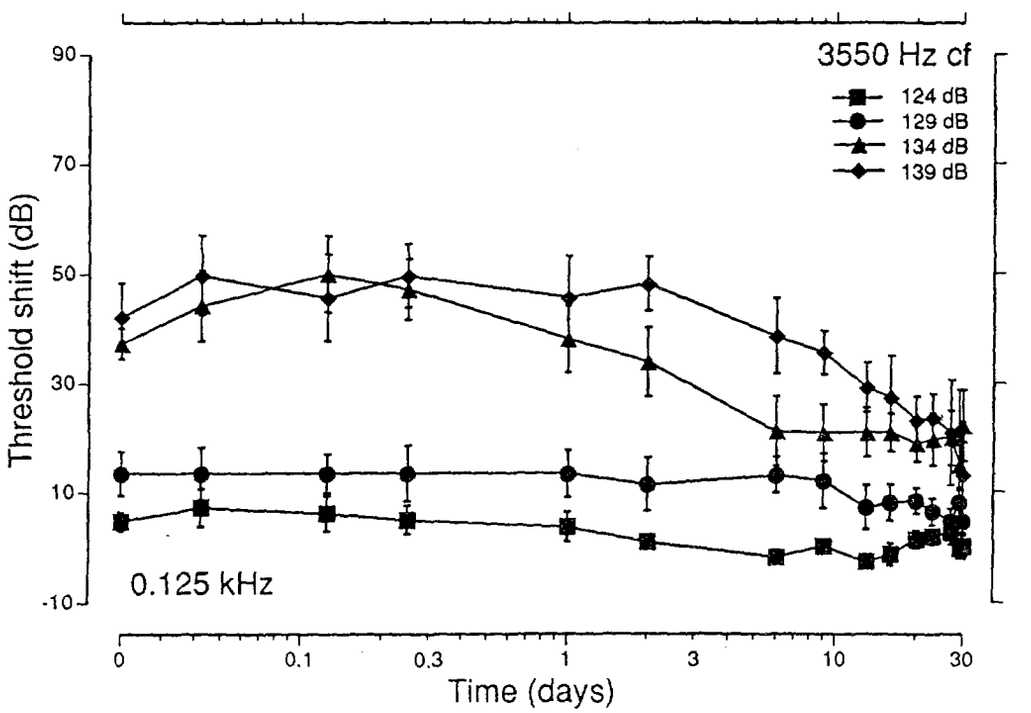

Figure 13. The mean threshold recovery curves for the groups exposed to the 3.550 kHz CF impulse at the indicated peak SPL for the 0.125 kHz audiometric test frequency.

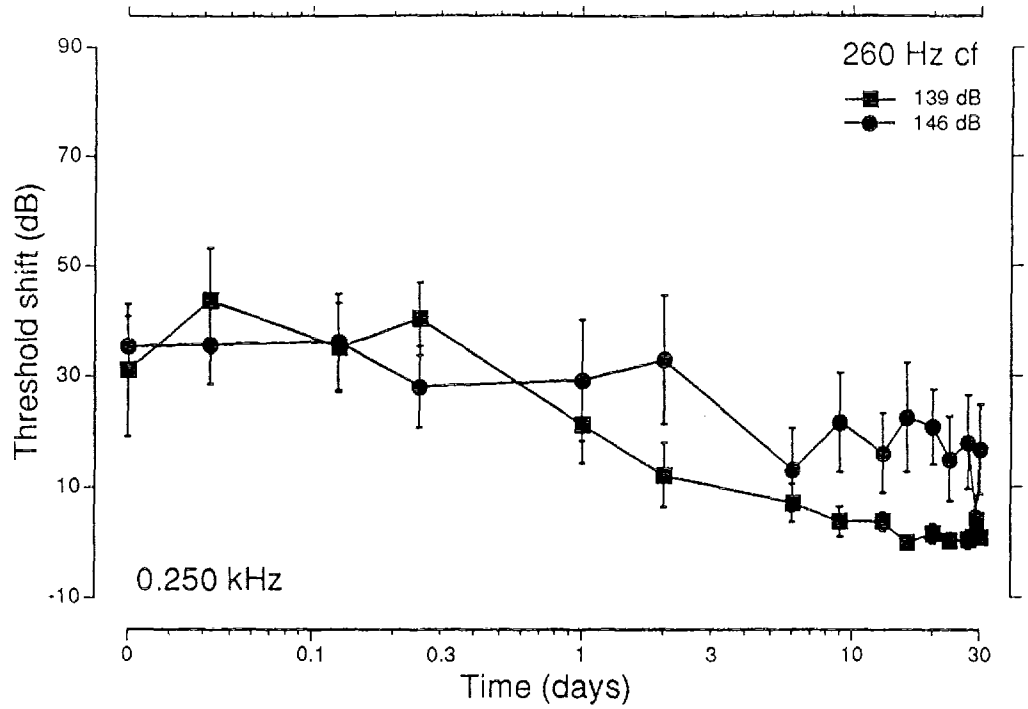

Figure 14. The mean threshold recovery curves for the groups exposed to the 0.260 kHz CF impulse at the indicated peak SPL for the 0.250 kHz audiometric test frequency.

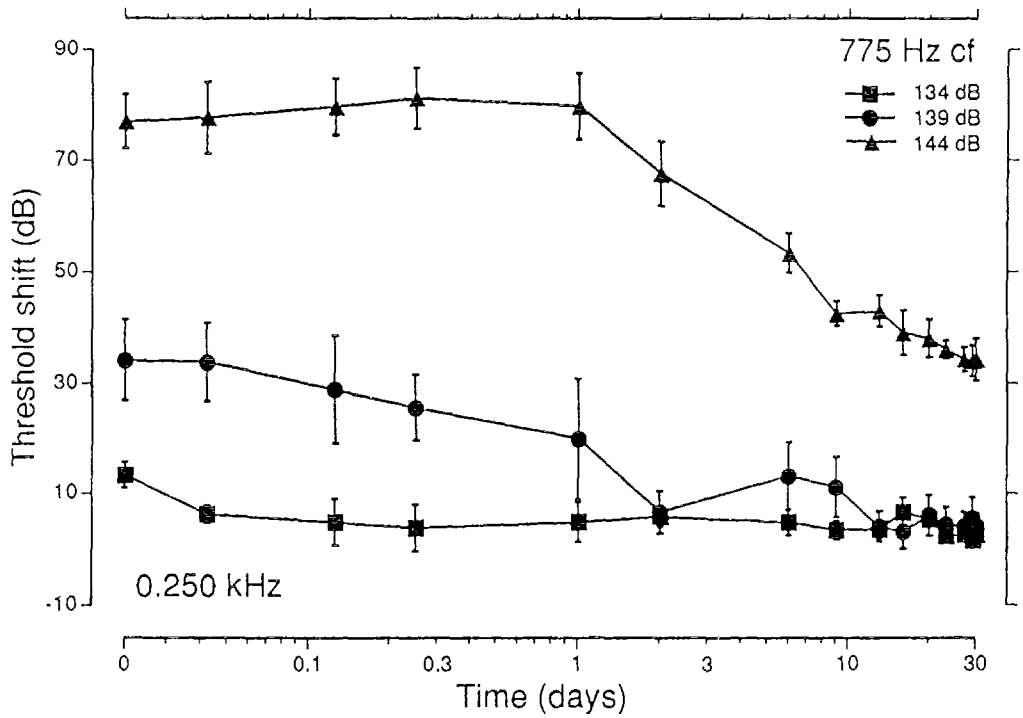

Figure 15. The mean threshold recovery curves for the groups exposed to the 0.775 kHz CF impulse at the indicated peak SPL for the 0.250 kHz audiometric test frequency.

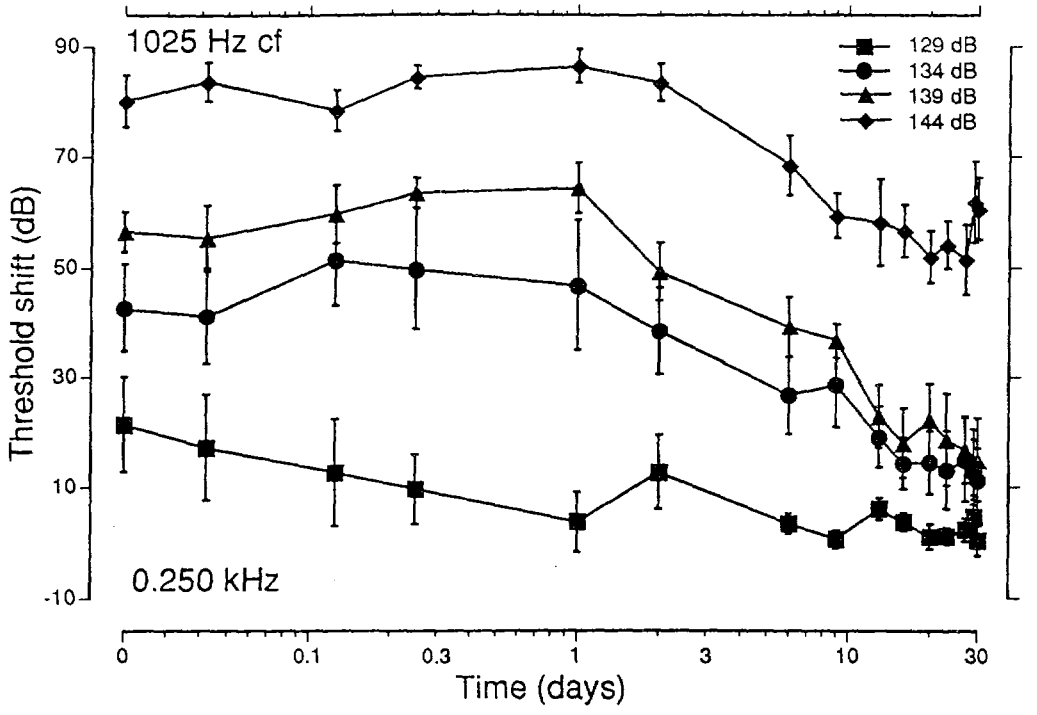

Figure 16. The mean threshold recovery curves for the groups exposed to the 1.025 kHz CF impulse at the indicated peak SPL for the 0.250 kHz audiometric test frequency.

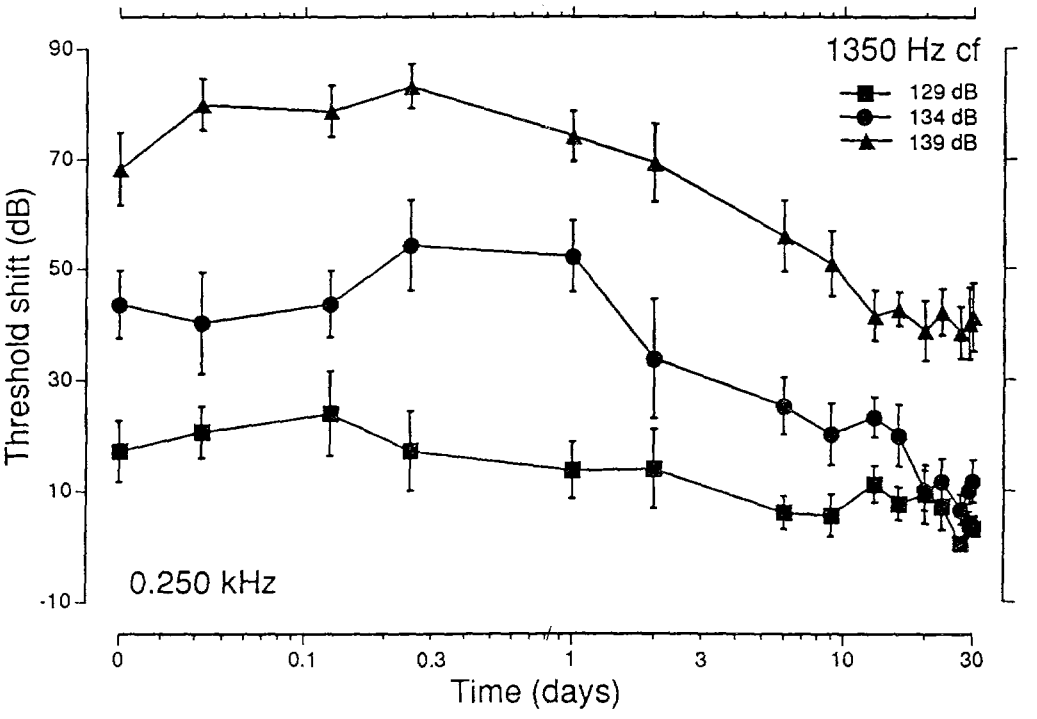

Figure 17. The mean threshold recovery curves for the groups exposed to the 1.350 kHz CF impulse at the indicated peak SPL for the 0.250 kHz audiometric test frequency.

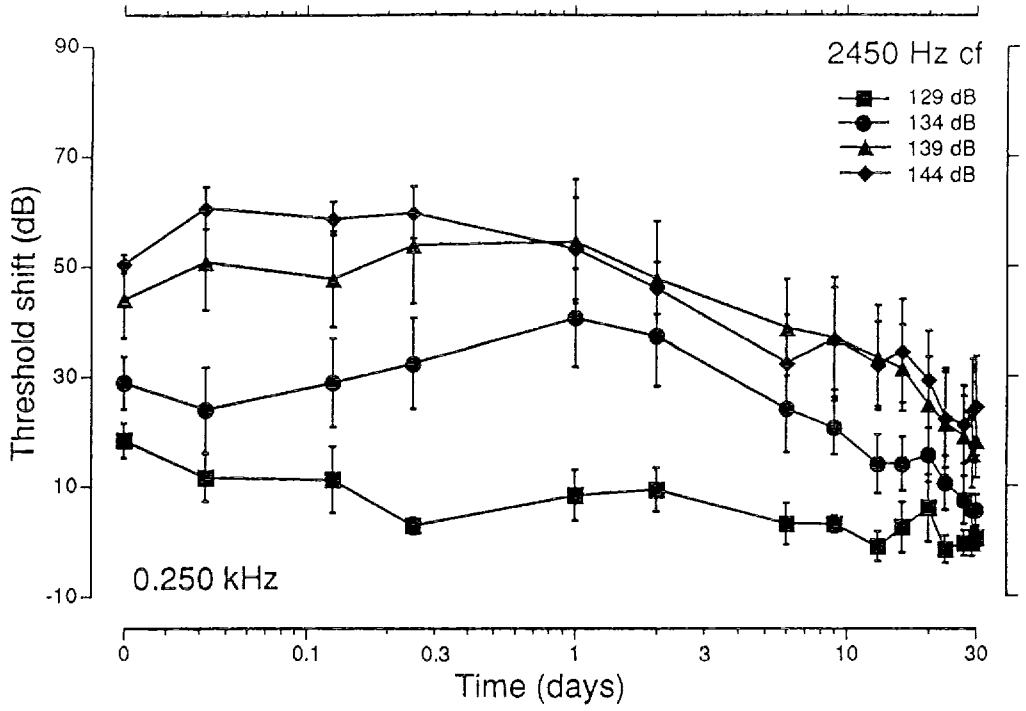

Figure 18. The mean threshold recovery curves for the groups exposed to the 2.450 kHz CF impulse at the indicated peak SPL for the 0.250 kHz audiometric test frequency.

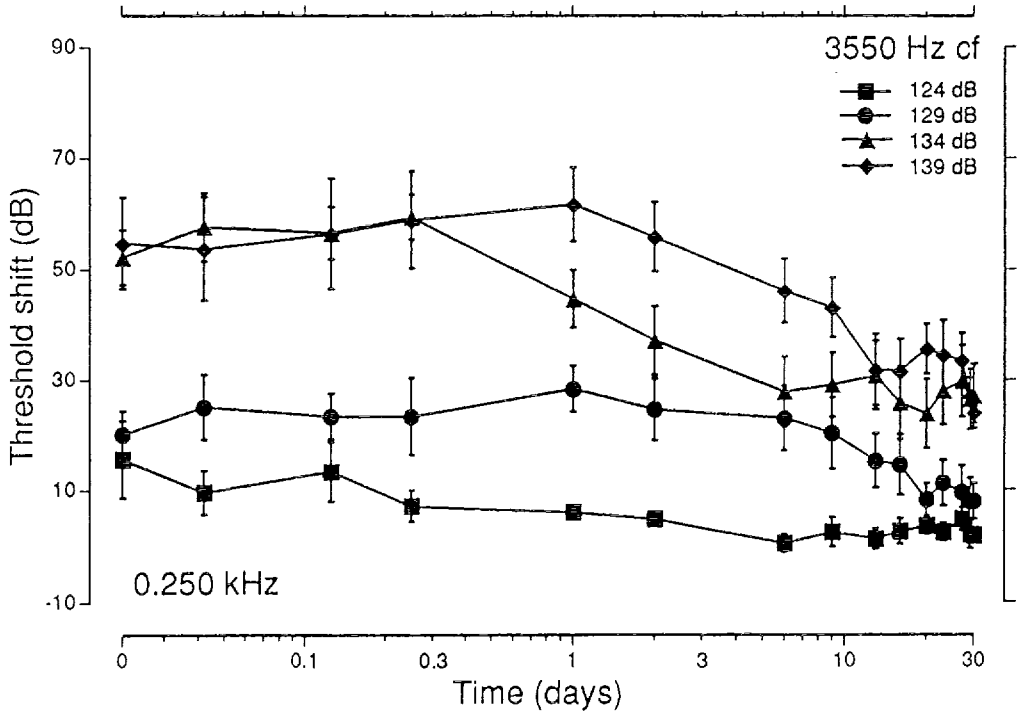

Figure 19. The mean threshold recovery curves for the groups exposed to the 3.550 kHz CF impulse at the indicated peak SPL for the 0.250 kHz audiometric test frequency.

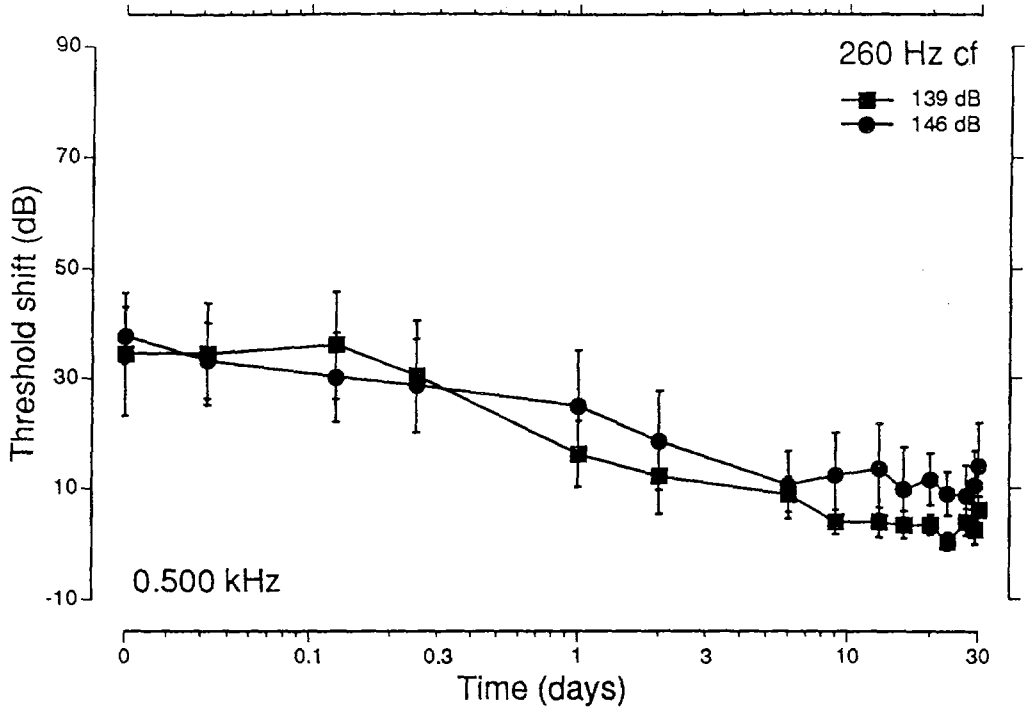

Figure 20. The mean threshold recovery curves for the groups exposed to the 0.260 kHz CF impulse at the indicated peak SPL for the 0.500 kHz audiometric test frequency.

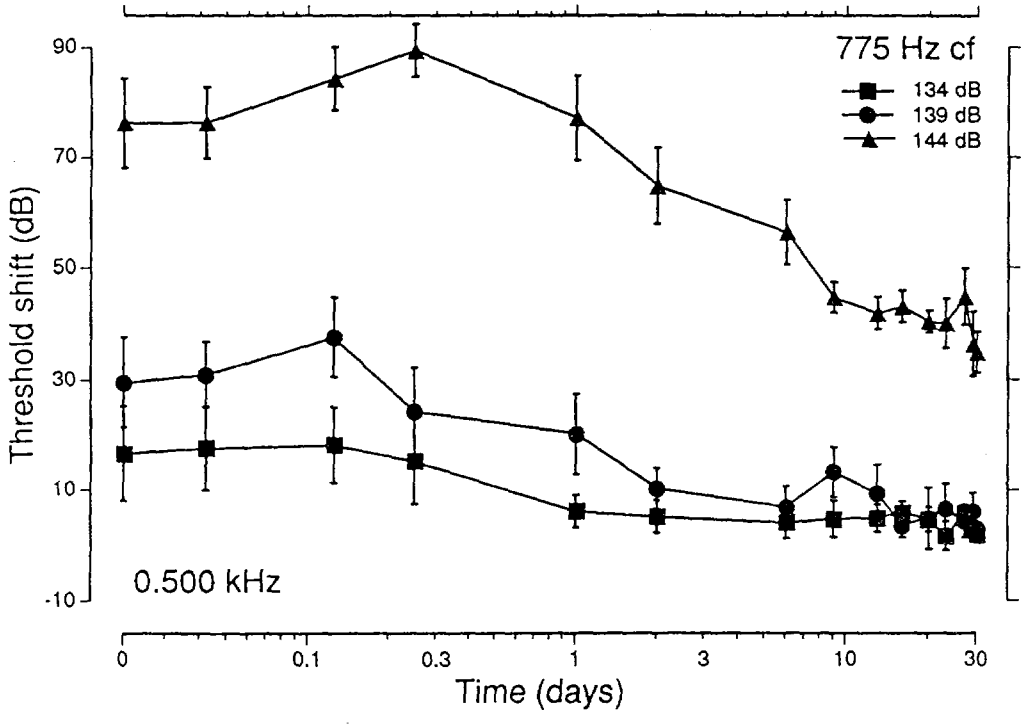

Figure 21. The mean threshold recovery curves for the groups exposed to the 0.775 kHz CF impulse at the indicated peak SPL for the 0.500 kHz audiometric test frequency.

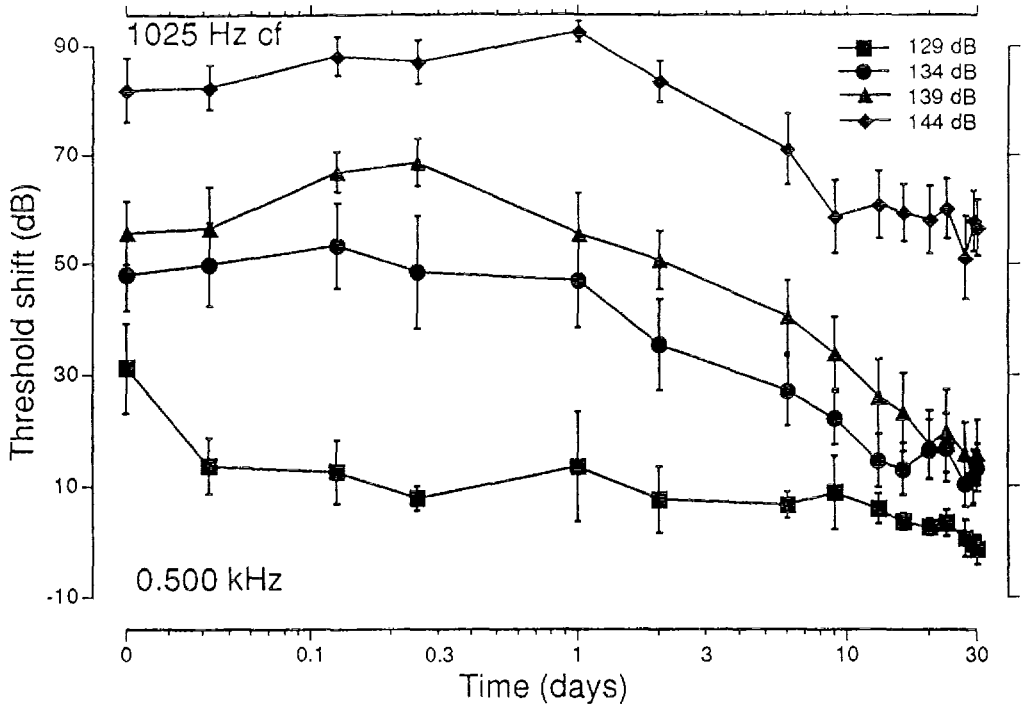

Figure 22. The mean threshold recovery curves for the groups exposed to the 1.025 kHz CF impulse at the indicated peak SPL for the 0.500 kHz audiometric test frequency.

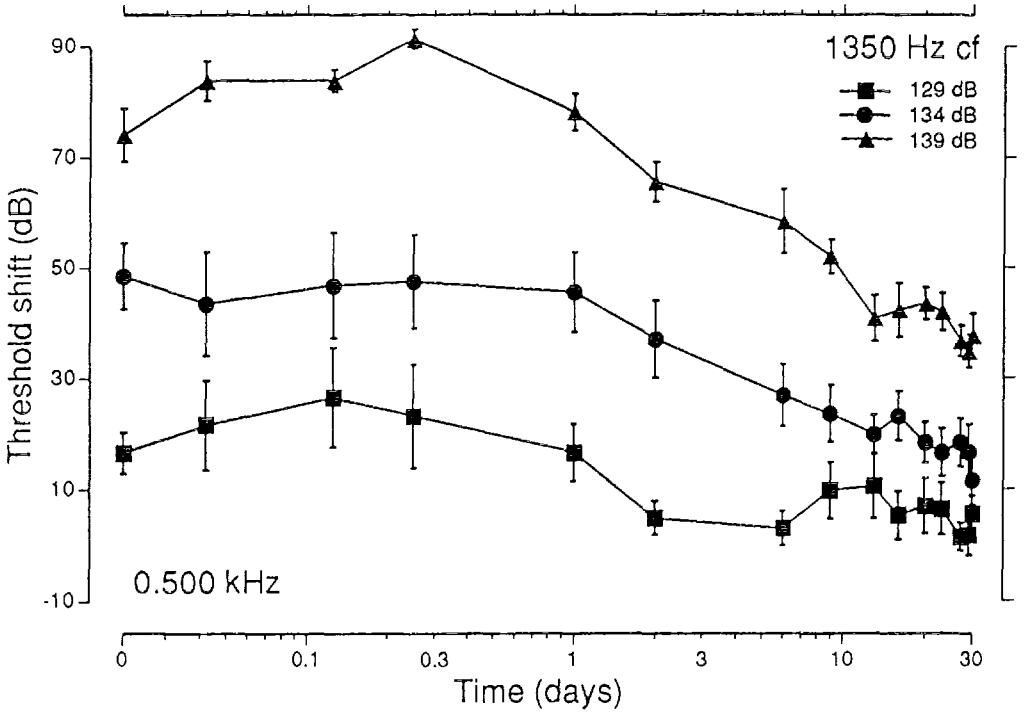

Figure 23. The mean threshold recovery curves for the groups exposed to the 1.350 kHz CF impulse at the indicated peak SPL for the 0.500 kHz audiometric test frequency.

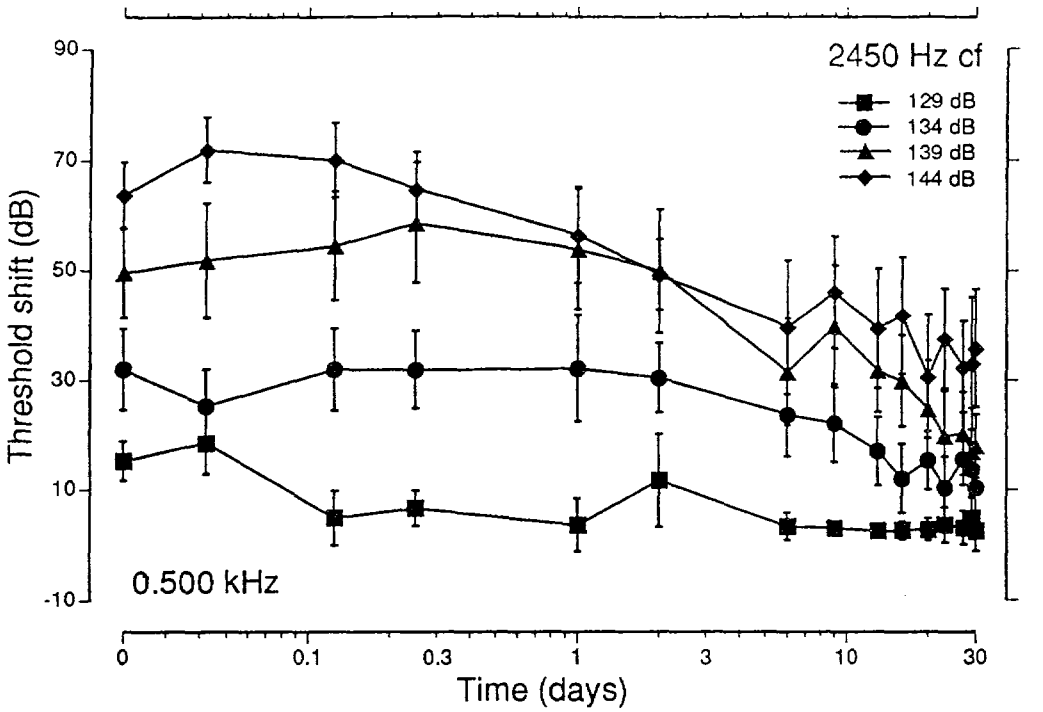

Figure 24. The mean threshold recovery curves for the groups exposed to the 2.450 kHz CF impulse at the indicated peak SPL for the 0.500 kHz audiometric test frequency.

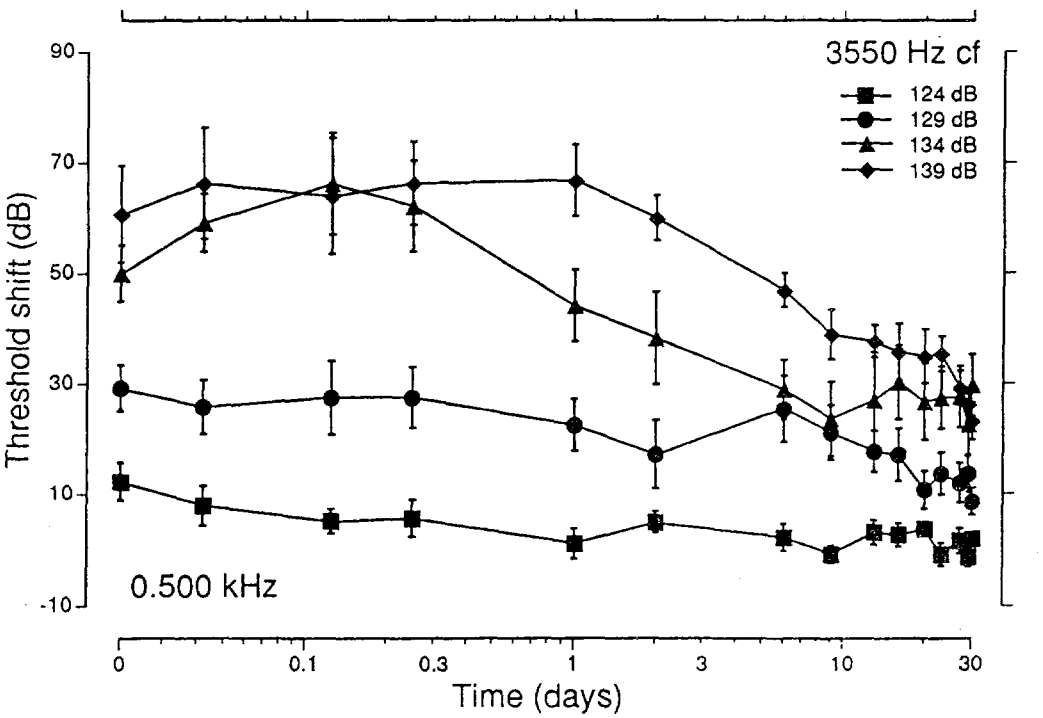

Figure 25. The mean threshold recovery curves for the groups exposed to the 3.550 kHz CF impulse at the indicated peak SPL for the 0.500 kHz audiometric test frequency.

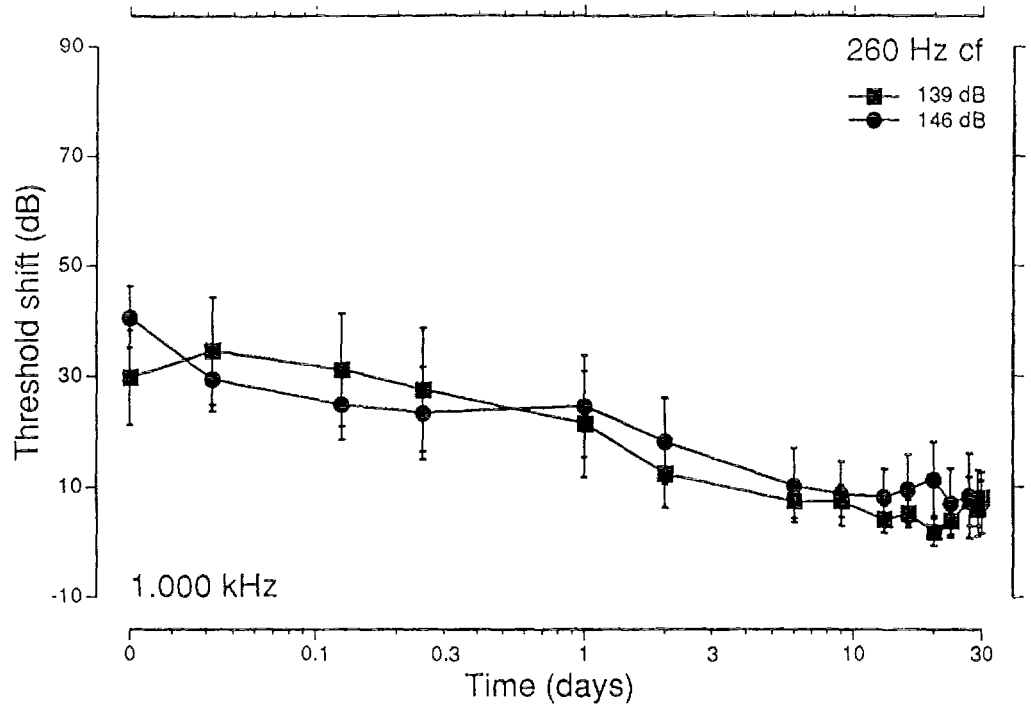

Figure 26. The mean threshold recovery curves for the groups exposed to the 0.260 kHz CF impulse at the indicated peak SPL for the 1.000 kHz audiometric test frequency.

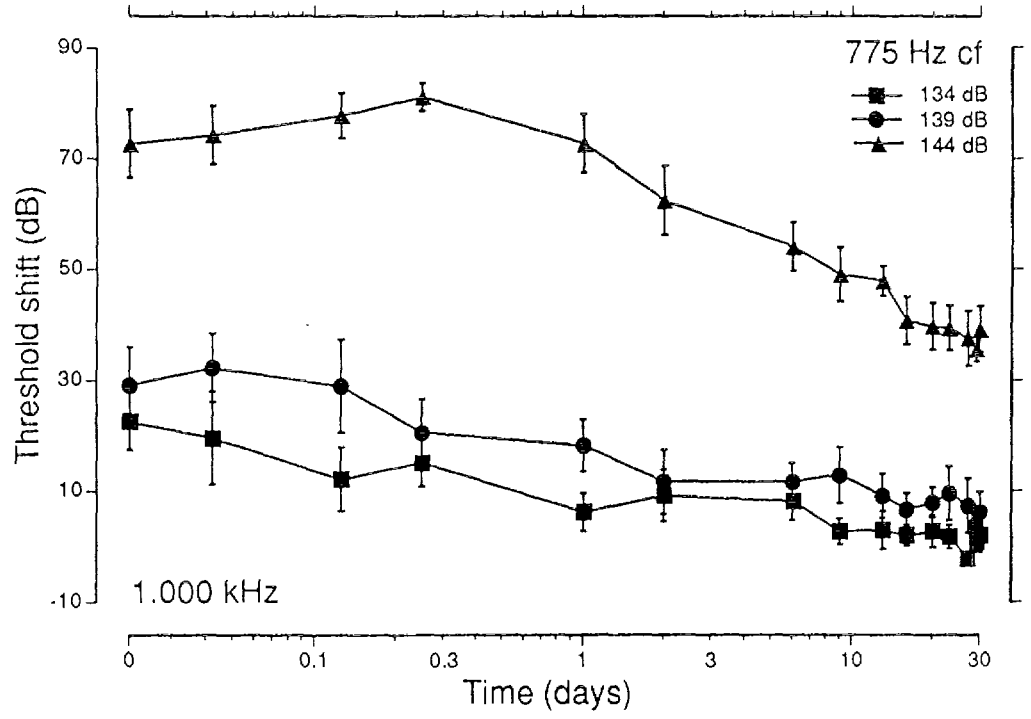

Figure 27. The mean threshold recovery curves for the groups exposed to the 0.775 kHz CF impulse at the indicated peak SPL for the 1.000 kHz audiometric test frequency.

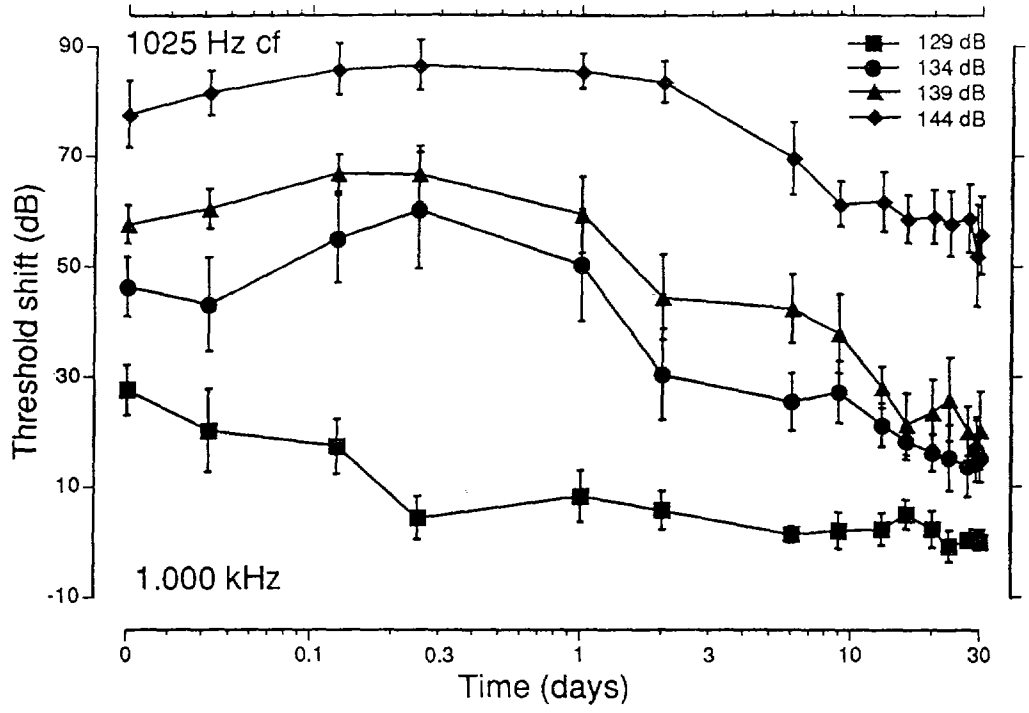

Figure 28. The mean threshold recovery curves for the groups exposed to the 1.025 kHz CF impulse at the indicated peak SPL for the 1.000 kHz audiometric test frequency.

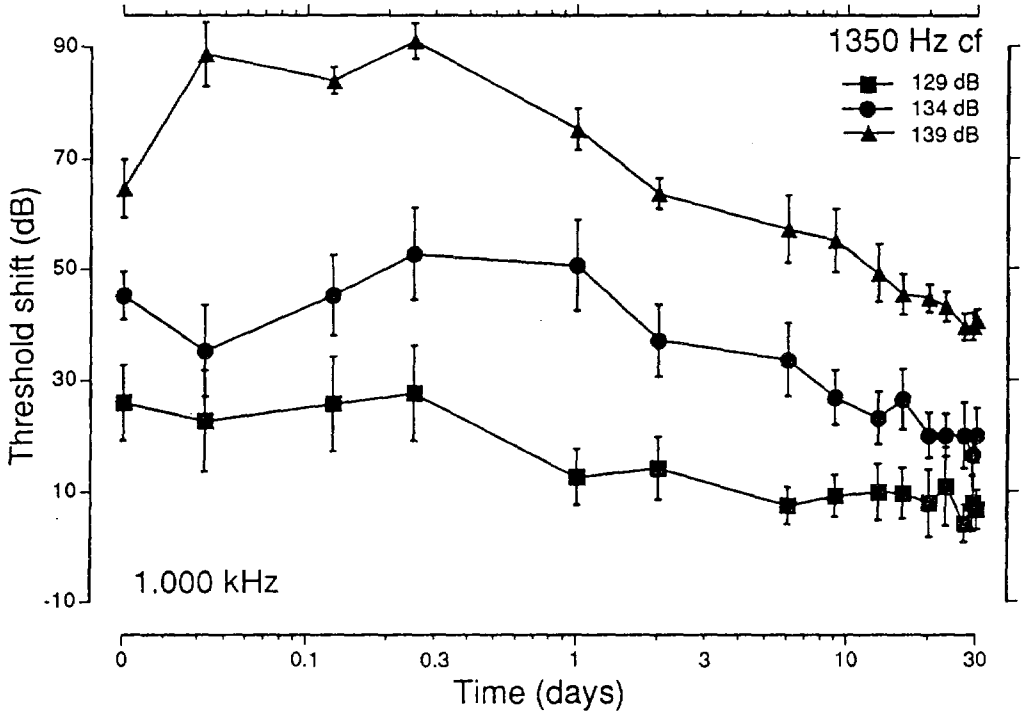

Figure 29. The mean threshold recovery curves for the groups exposed to the 1.350 kHz CF impulse at the indicated peak SPL for the 1.000 kHz audiometric test frequency.

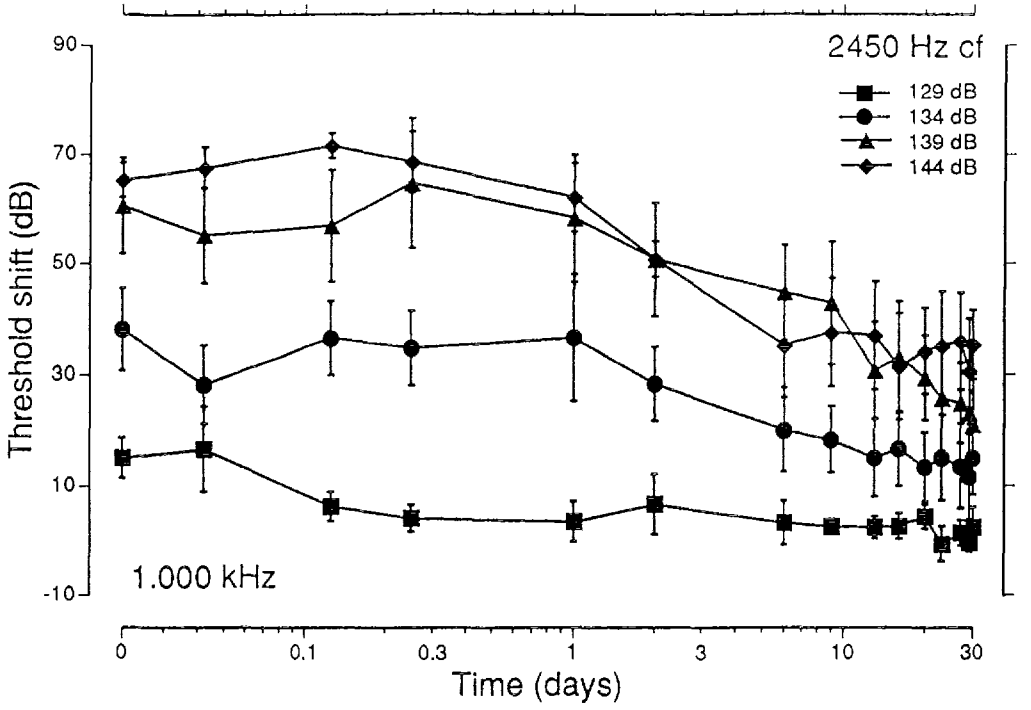

Figure 30. The mean threshold recovery curves for the groups exposed to the 2.450 kHz CF impulse at the indicated peak SPL for the 1.000 kHz audiometric test frequency.

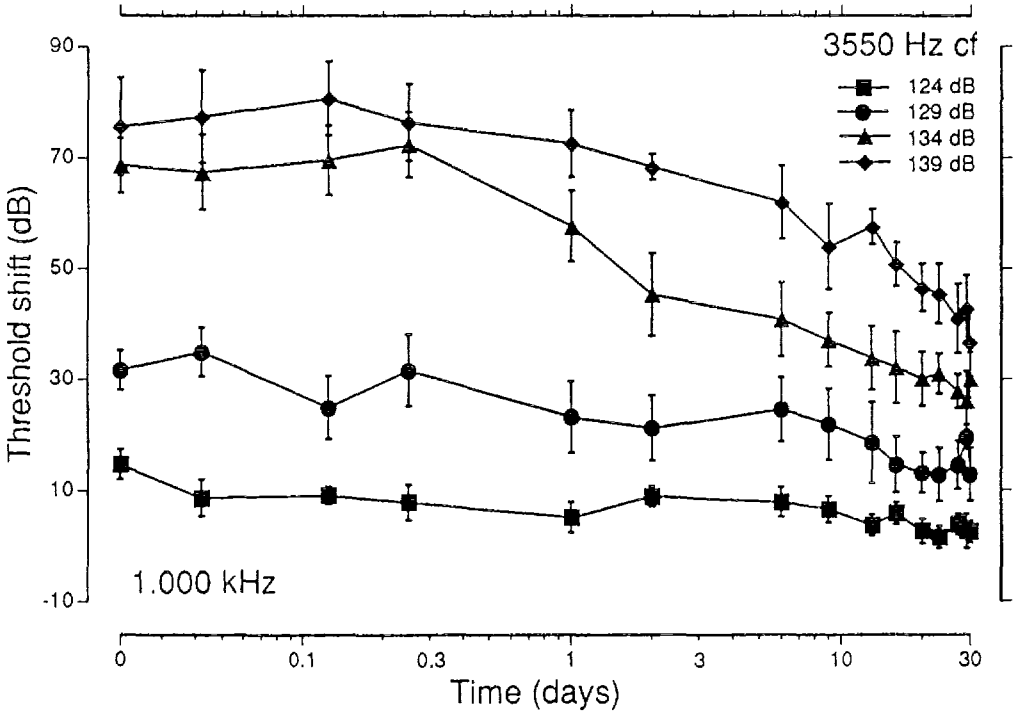

Figure 31. The mean threshold recovery curves for the groups exposed to the 3.550 kHz CF impulse at the indicated peak SPL for the 1.000 kHz audiometric test frequency.

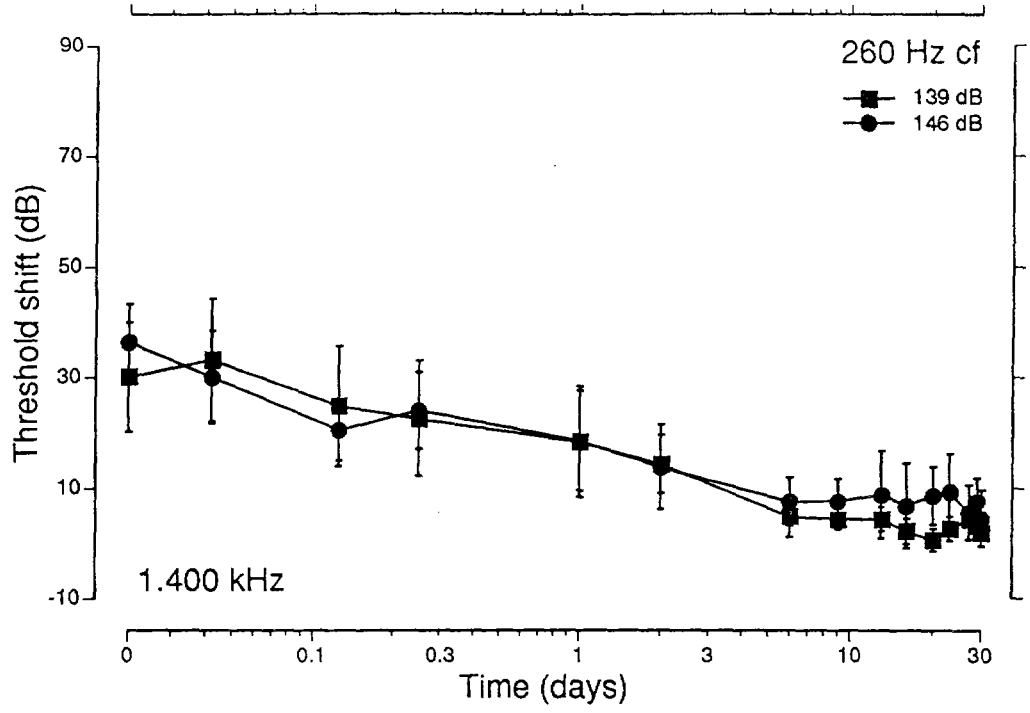

Figure 32. The mean threshold recovery curves for the groups exposed to the 0.260 kHz CF impulse at the indicated peak SPL for the 1.400 kHz audiometric test frequency.

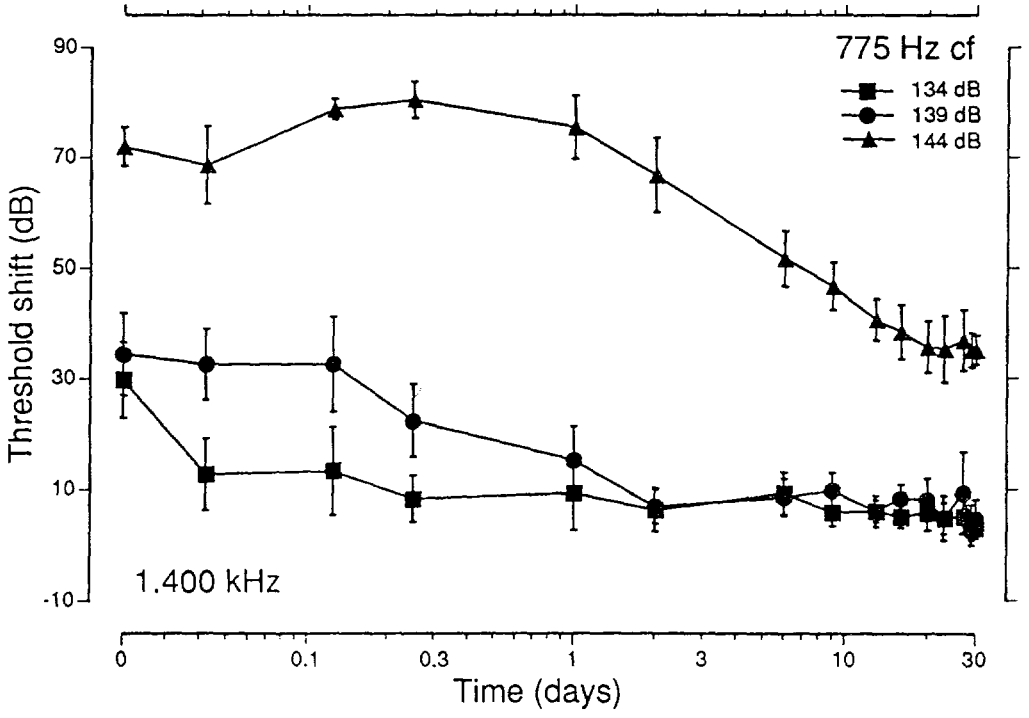

Figure 33. The mean threshold recovery curves for the groups exposed to the 0.775 kHz CF impulse at the indicated peak SPL for the 1.400 kHz audiometric test frequency.

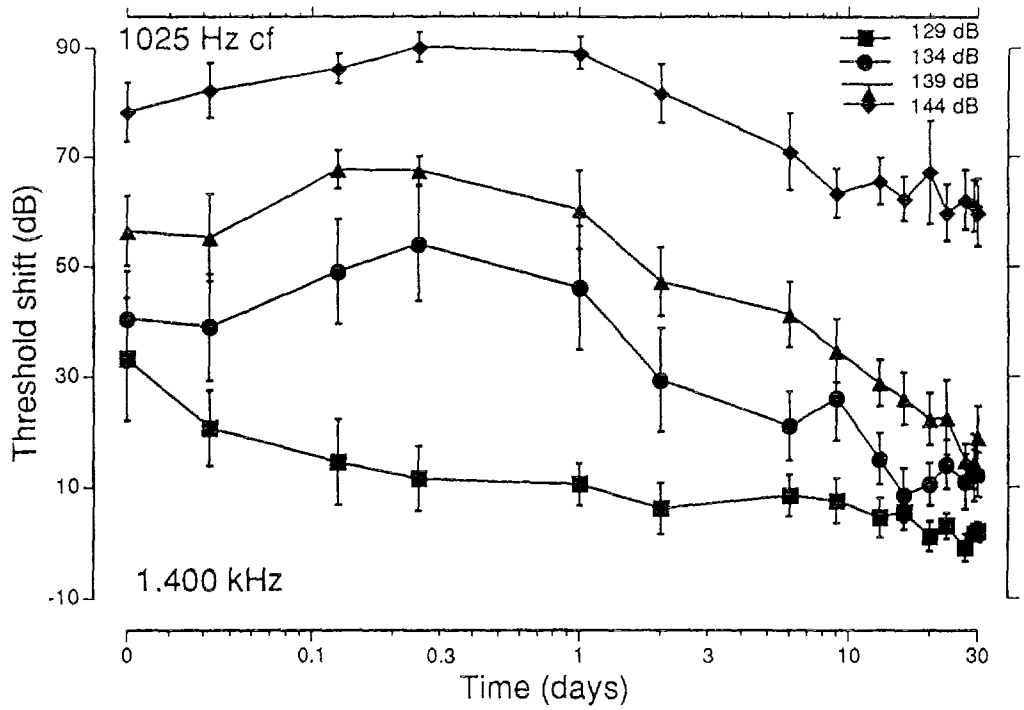

Figure 34. The mean threshold recovery curves for the groups exposed to the 1.025 kHz CF impulse at the indicated peak SPL for the 1.400 kHz audiometric test frequency.

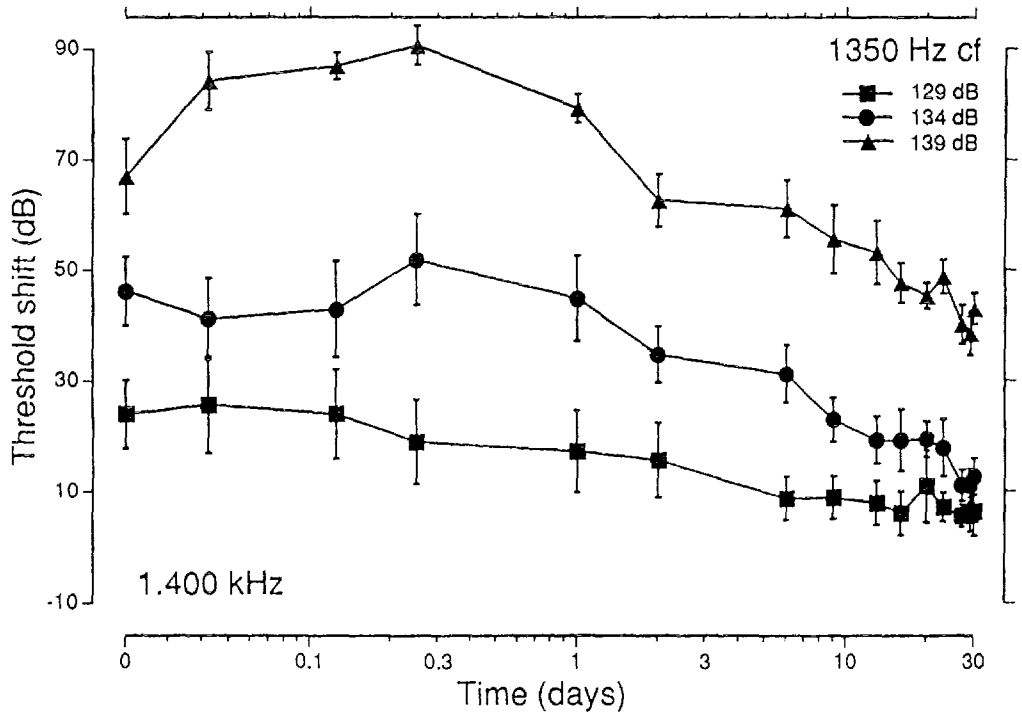

Figure 35. The mean threshold recovery curves for the groups exposed to the 1.350 kHz CF impulse at the indicated peak SPL for the 1.400 kHz audiometric test frequency.

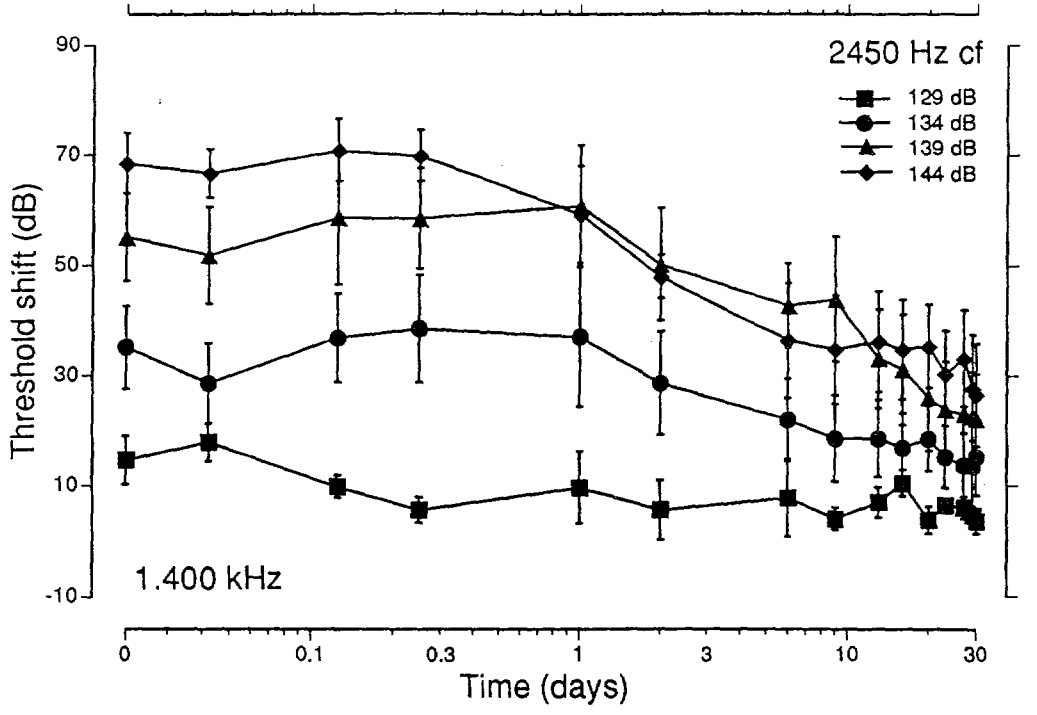

Figure 36. The mean threshold recovery curves for the groups exposed to the 2.450 kHz CF impulse at the indicated peak SPL for the 1.400 kHz audiometric test frequency.

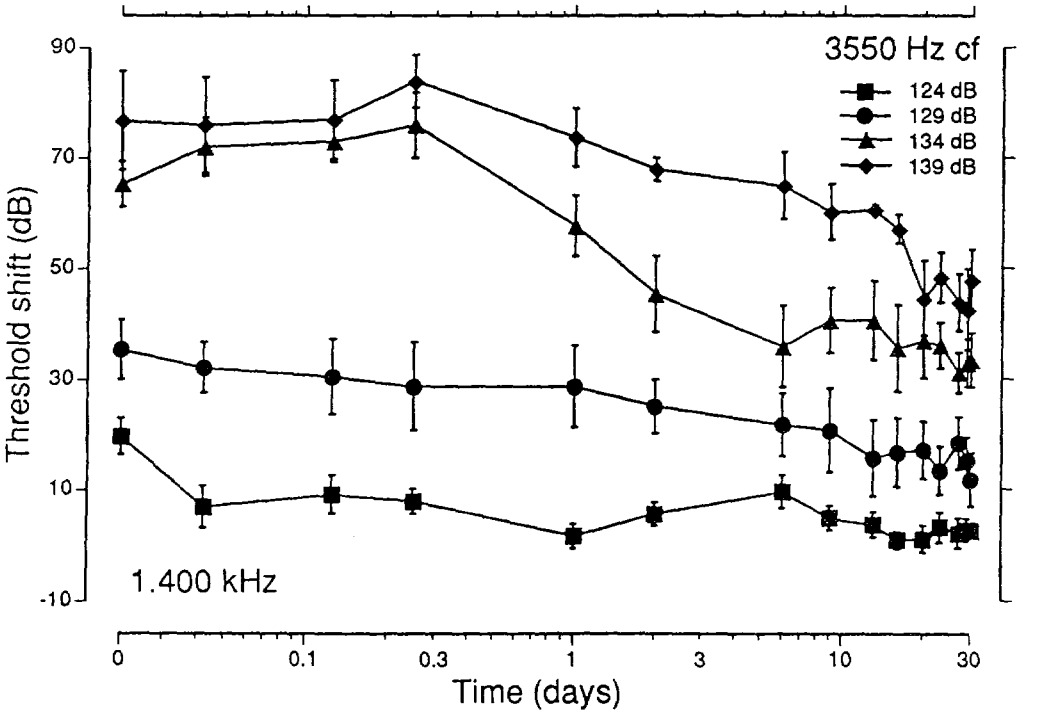

Figure 37. The mean threshold recovery curves for the groups exposed to the 3.550 kHz CF impulse at the indicated peak SPL for the 1.400 kHz audiometric test frequency.

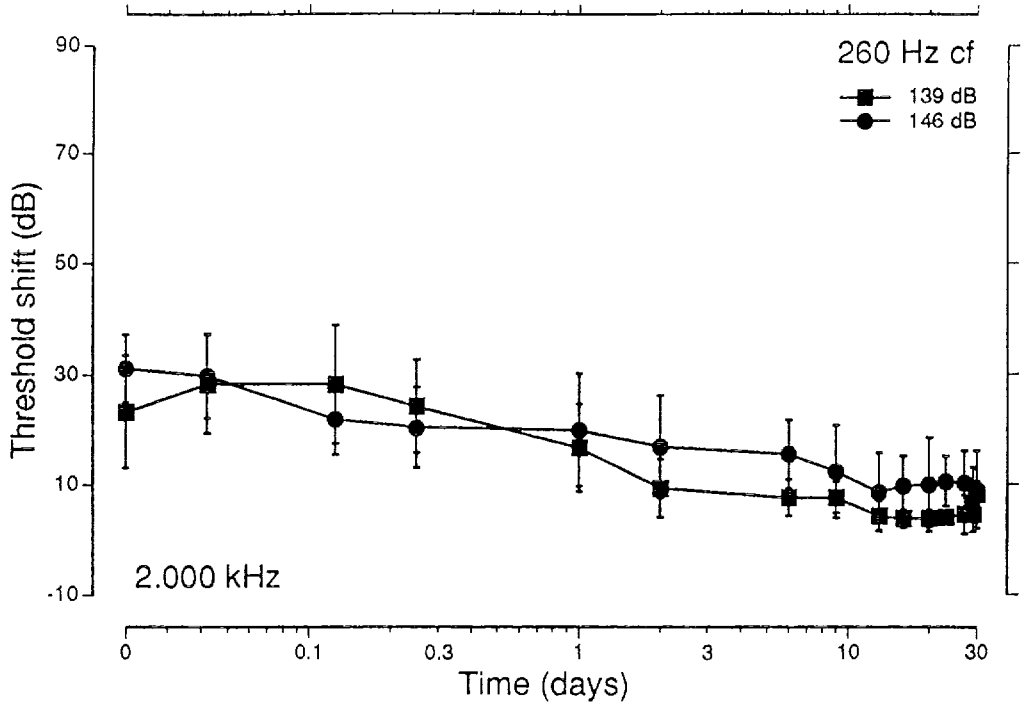

Figure 38. The mean threshold recovery curves for the groups exposed to the 0.260 kHz CF impulse at the indicated peak SPL for the 2.000 kHz audiometric test frequency.

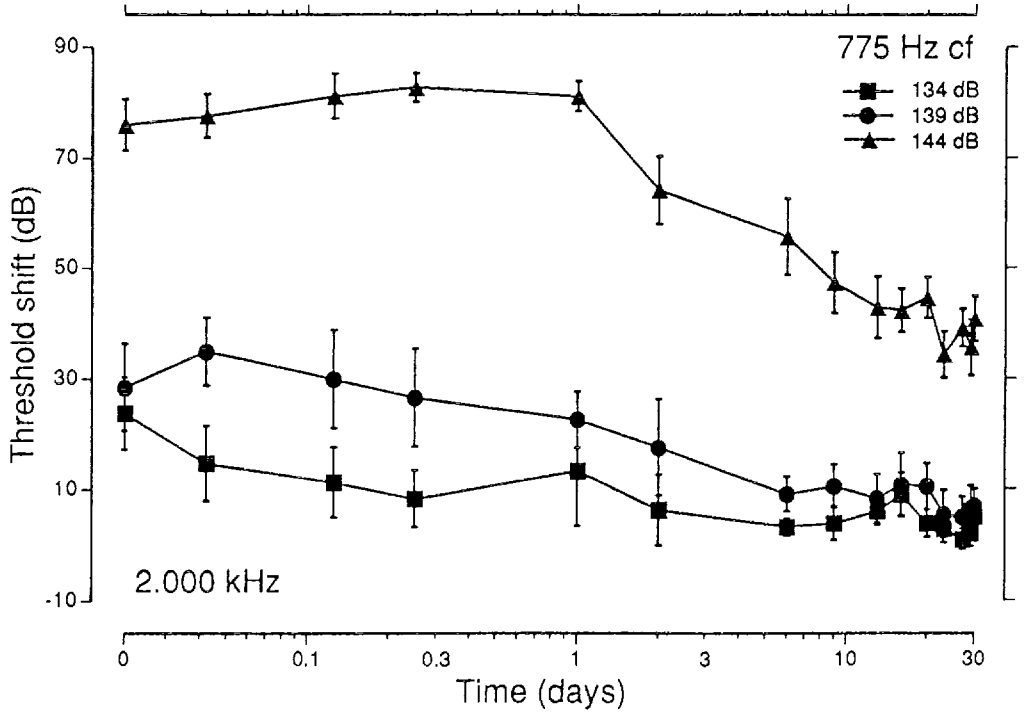

Figure 39. The mean threshold recovery curves for the groups exposed to the 0.775 kHz CF impulse at the indicated peak SPL for the 2.000 kHz audiometric test frequency.

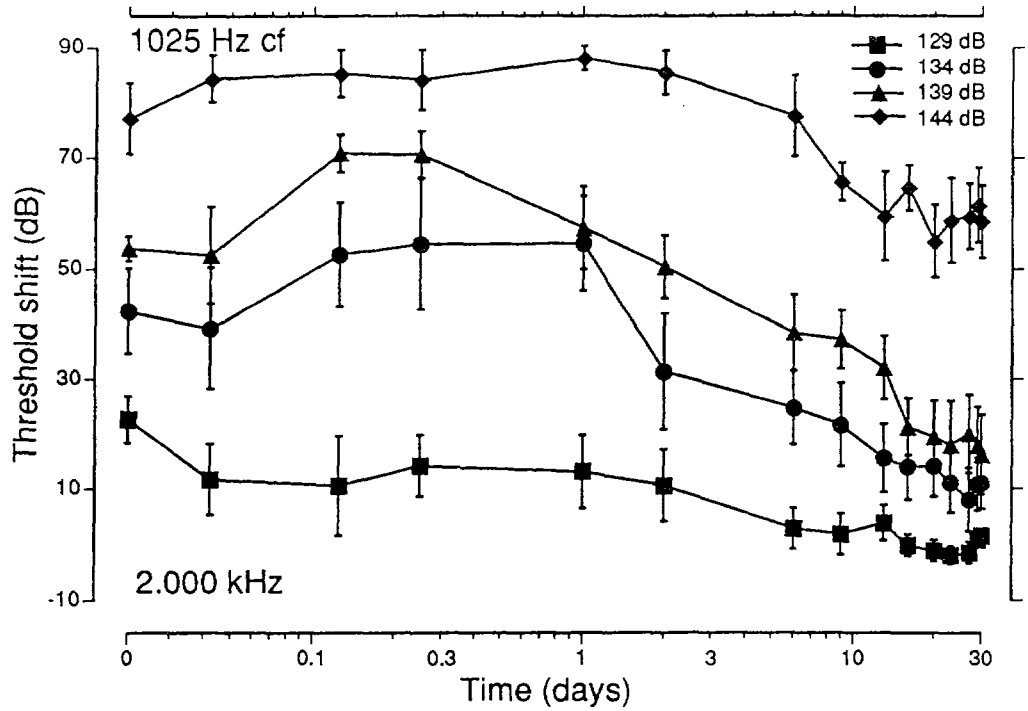

Figure 40. The mean threshold recovery curves for the groups exposed to the 1.025 kHz CF impulse at the indicated peak SPL for the 2.000 kHz audiometric test frequency.

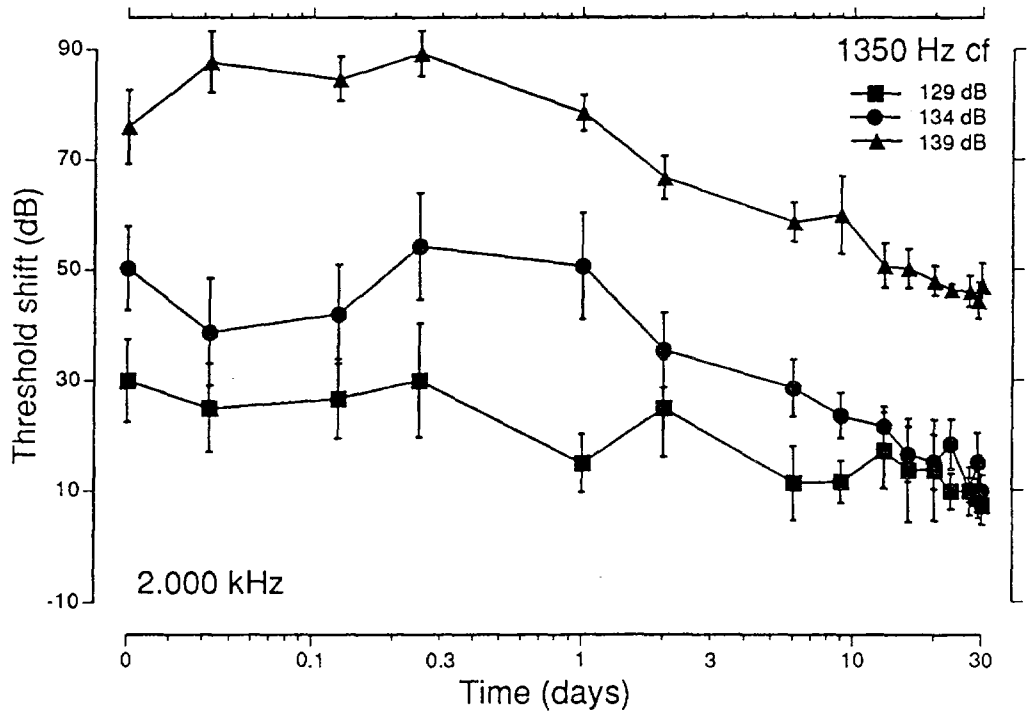

Figure 41. The mean threshold recovery curves for the groups exposed to the 1.350 kHz CF impulse at the indicated peak SPL for the 2.000 kHz audiometric test frequency.

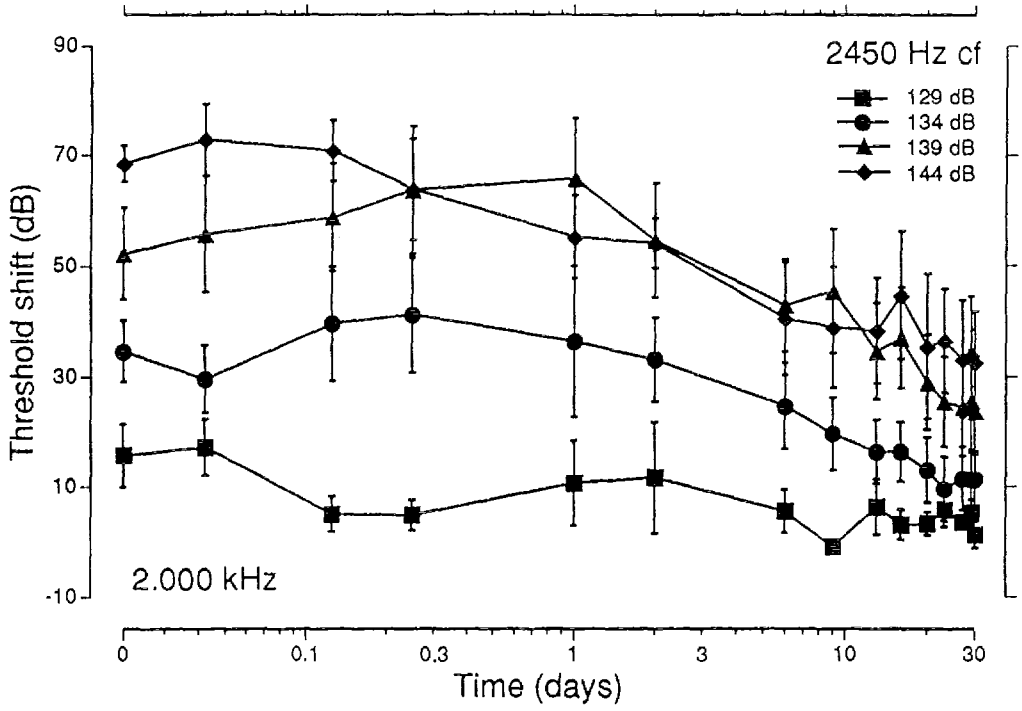

Figure 42. The mean threshold recovery curves for the groups exposed to the 2.450 kHz CF impulse at the indicated peak SPL for the 2.000 kHz audiometric test frequency.

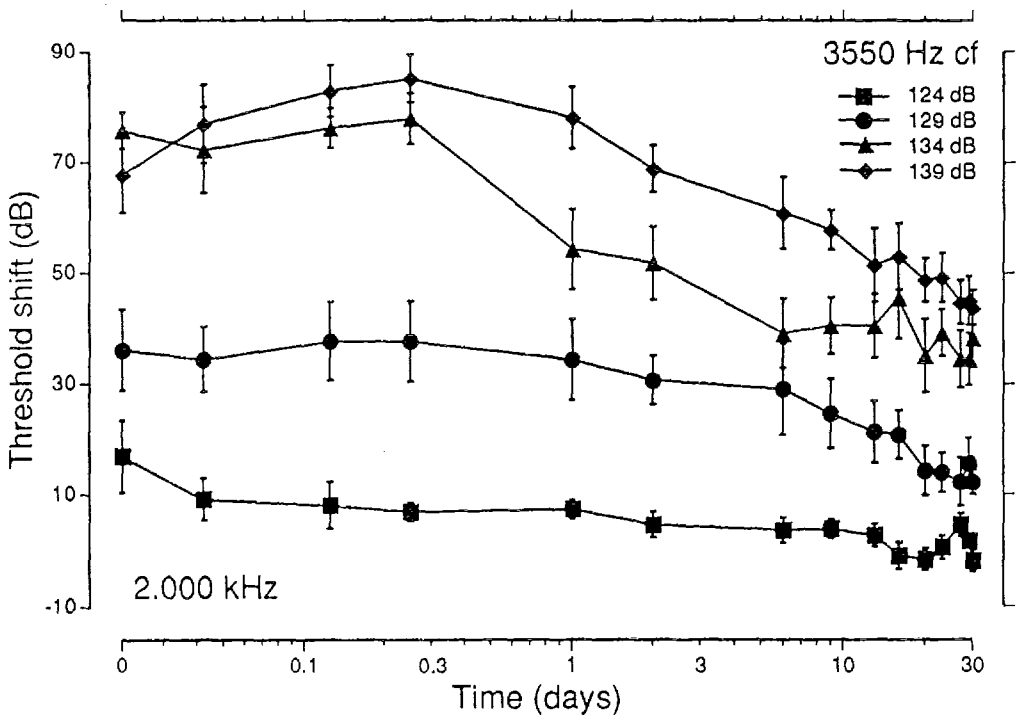

Figure 43. The mean threshold recovery curves for the groups exposed to the 3.550 kHz CF impulse at the indicated peak SPL for the 2.000 kHz audiometric test frequency.

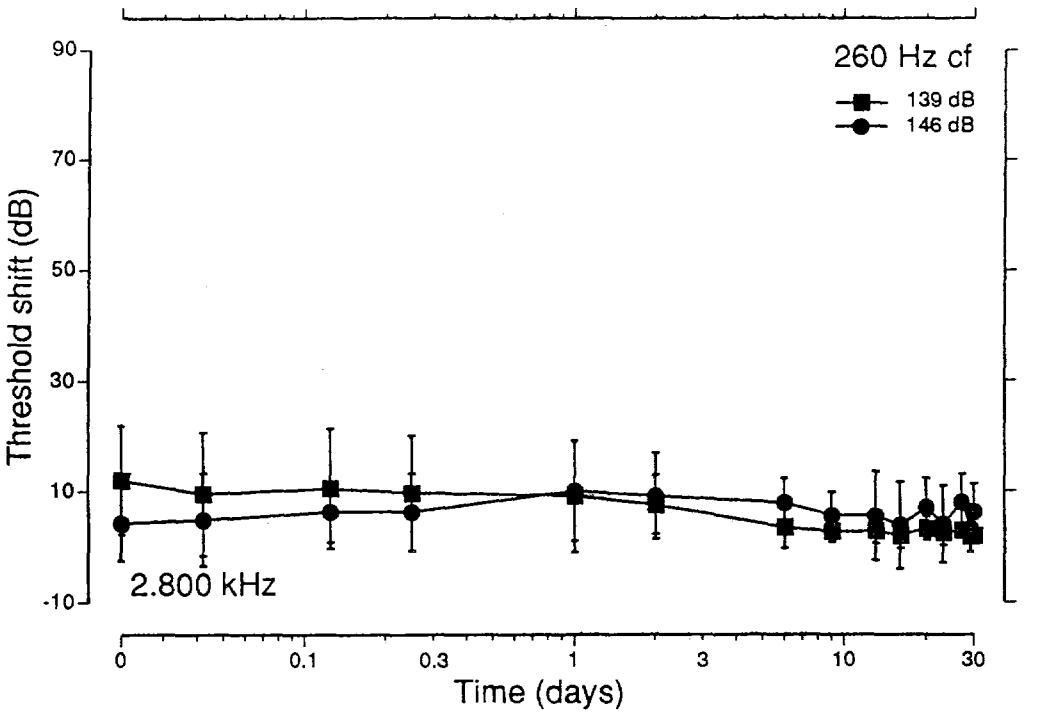

Figure 44. The mean threshold recovery curves for the groups exposed to the 0.260 kHz CF impulse at the indicated peak SPL for the 2.800 kHz audiometric test frequency.

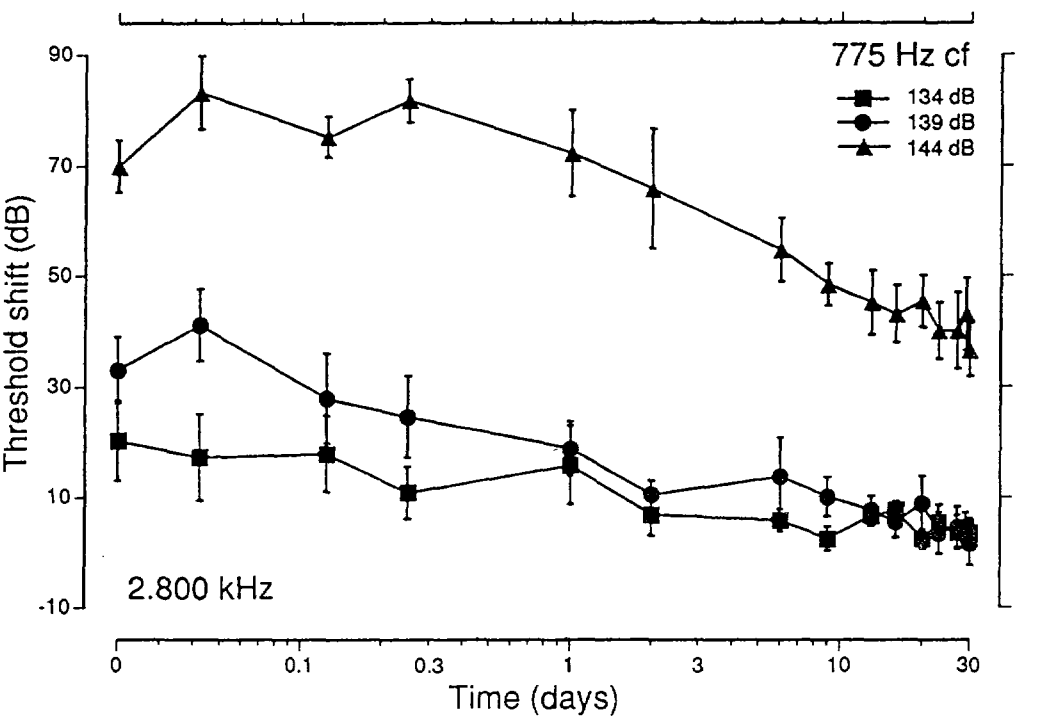

Figure 45. The mean threshold recovery curves for the groups exposed to the 0.775 kHz CF impulse at the indicated peak SPL for the 2.800 kHz audiometric test frequency.

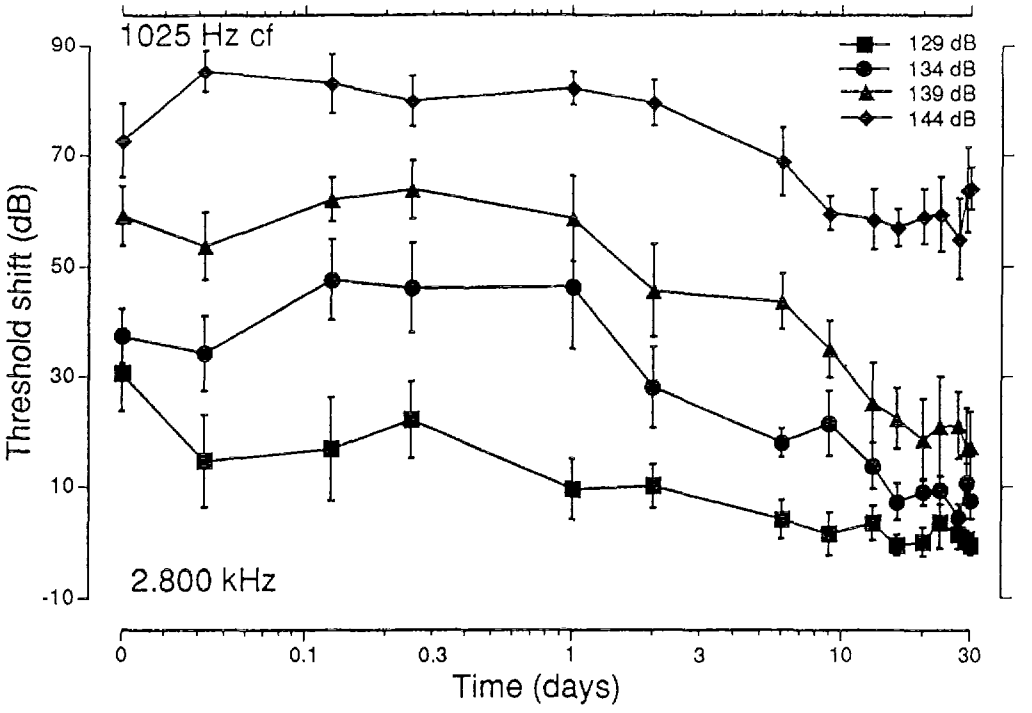

Figure 46. The mean threshold recovery curves for the groups exposed to the 1.025 kHz CF impulse at the indicated peak SPL for the 2.800 kHz audiometric test frequency.

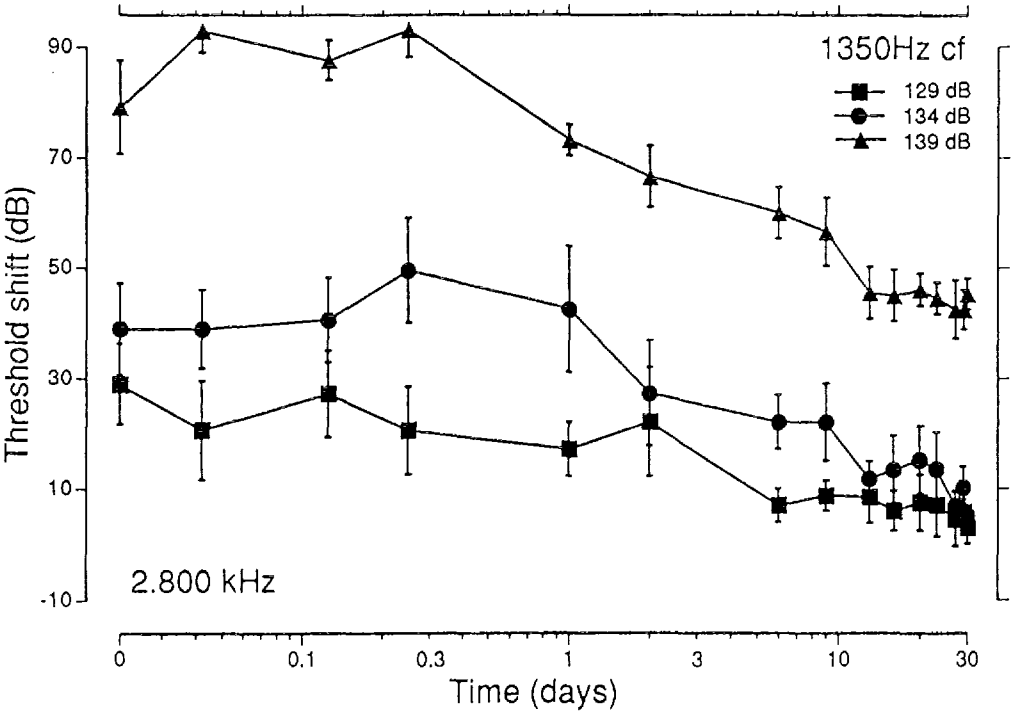

Figure 47. The mean threshold recovery curves for the groups exposed to the 1.350 kHz CF impulse at the indicated peak SPL for the 2.800 kHz audiometric test frequency.

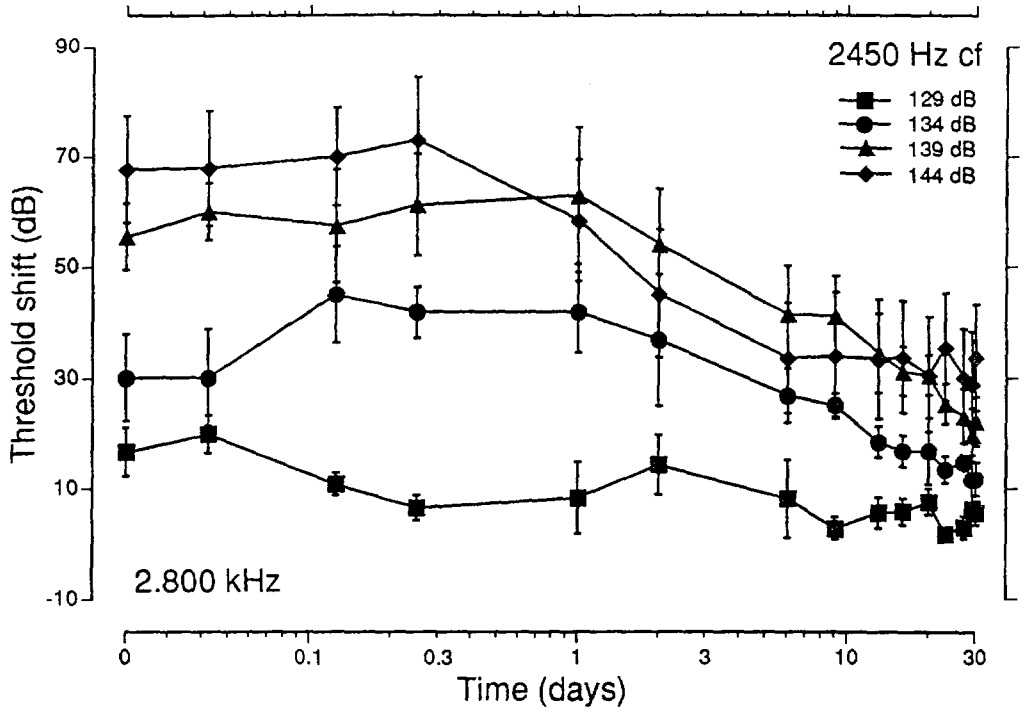

Figure 48. The mean threshold recovery curves for the groups exposed to the 2.450 kHz CF impulse at the indicated peak SPL for the 2.800 kHz audiometric test frequency.

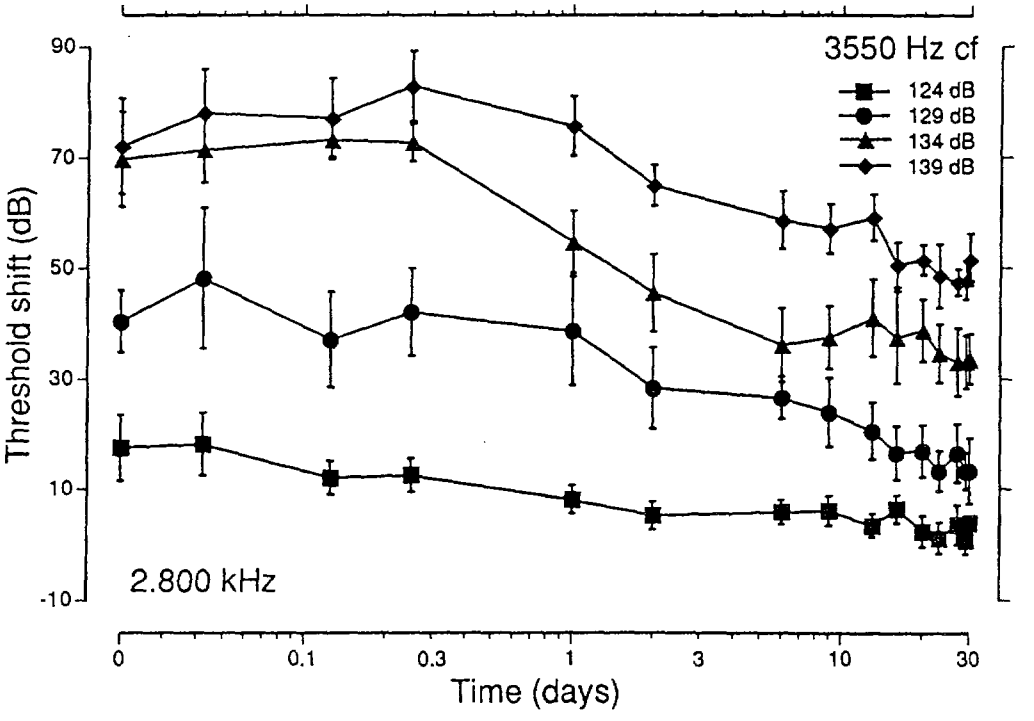

Figure 49. The mean threshold recovery curves for the groups exposed to the 3.550 kHz CF impulse at the indicated peak SPL for the 2.800 kHz audiometric test frequency.

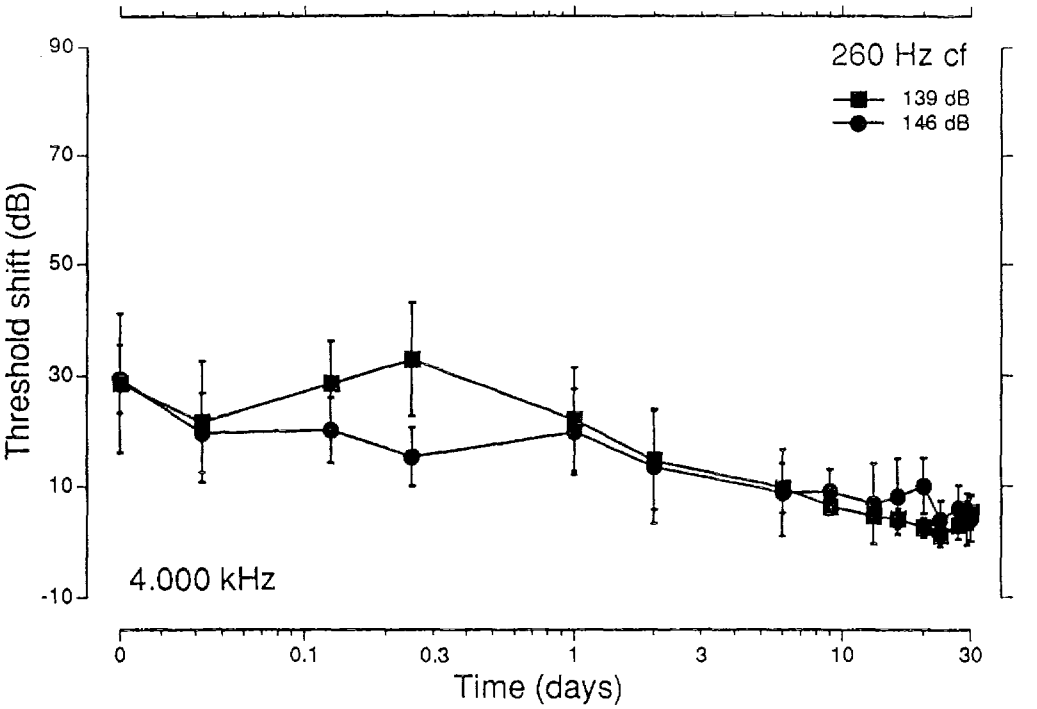

Figure 50. The mean threshold recovery curves for the groups exposed to the 0.260 kHz CF impulse at the indicated peak SPL for the 4.000 kHz audiometric test frequency.

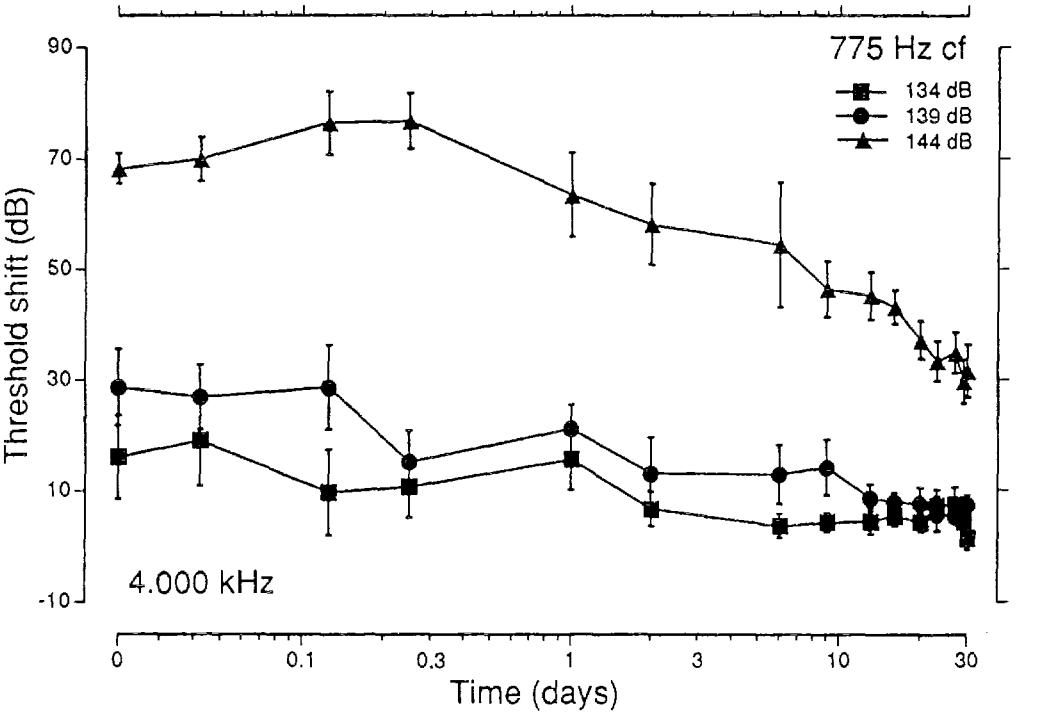

Figure 51. The mean threshold recovery curves for the groups exposed to the 0.775 kHz CF impulse at the indicated peak SPL for the 4.000 kHz audiometric test frequency.

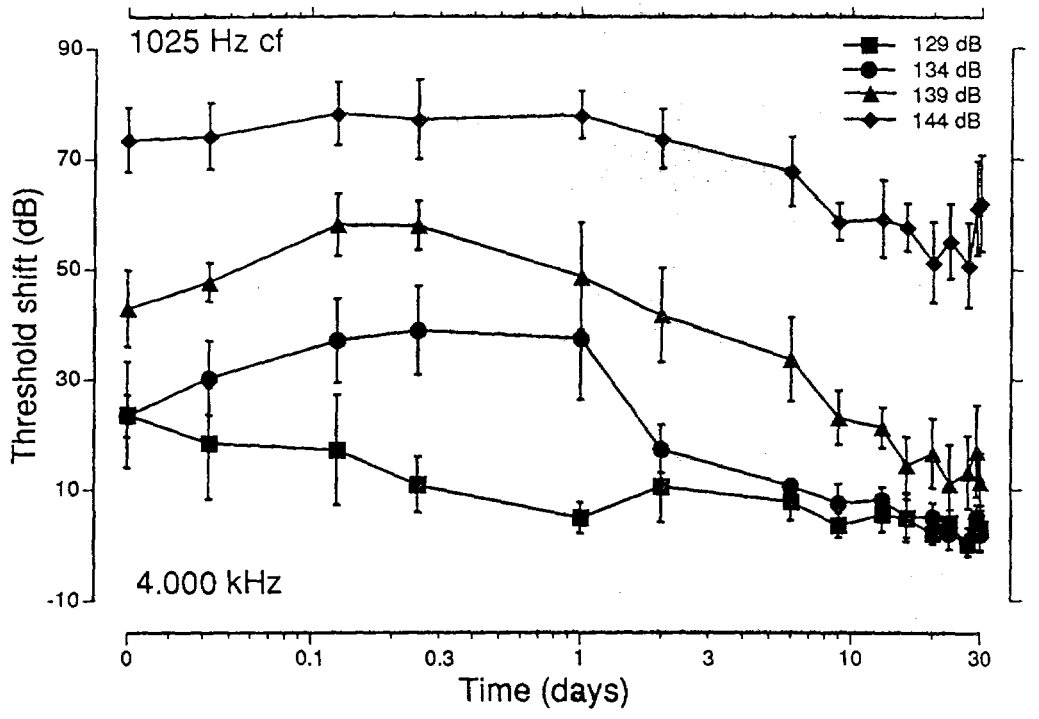

Figure 52. The mean threshold recovery curves for the groups exposed to the 1.025 kHz CF impulse at the indicated peak SPL for the 4.000 kHz audiometric test frequency.

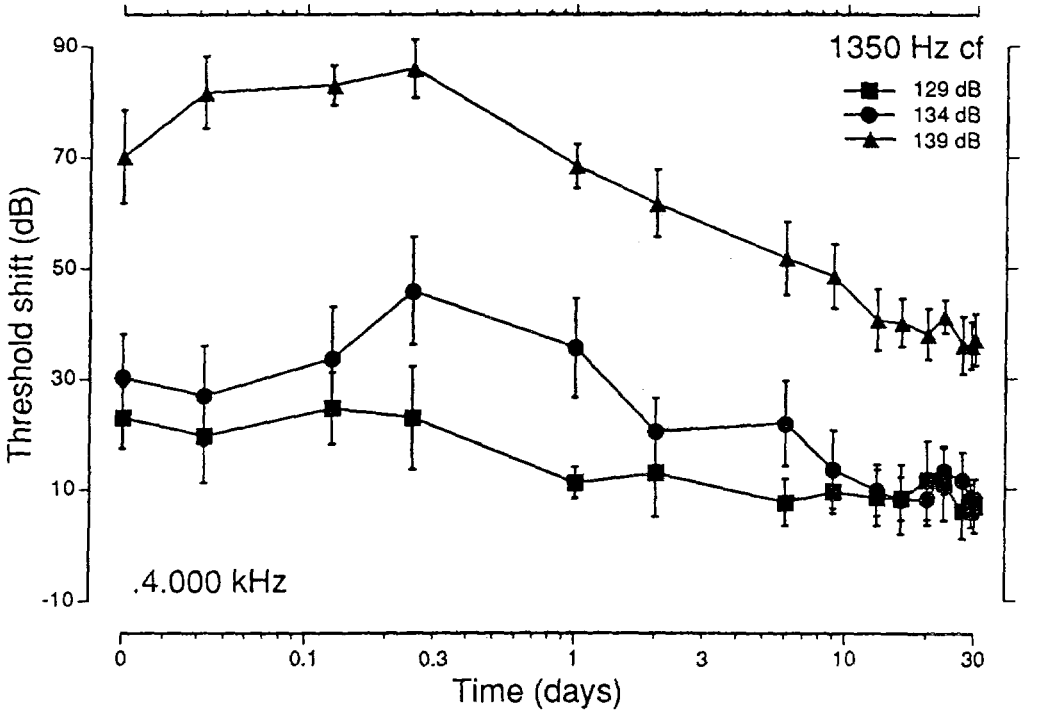

Figure 53. The mean threshold recovery curves for the groups exposed to the 1.775 kHz CF impulse at the indicated peak SPL for the 4.000 kHz audiometric test frequency.

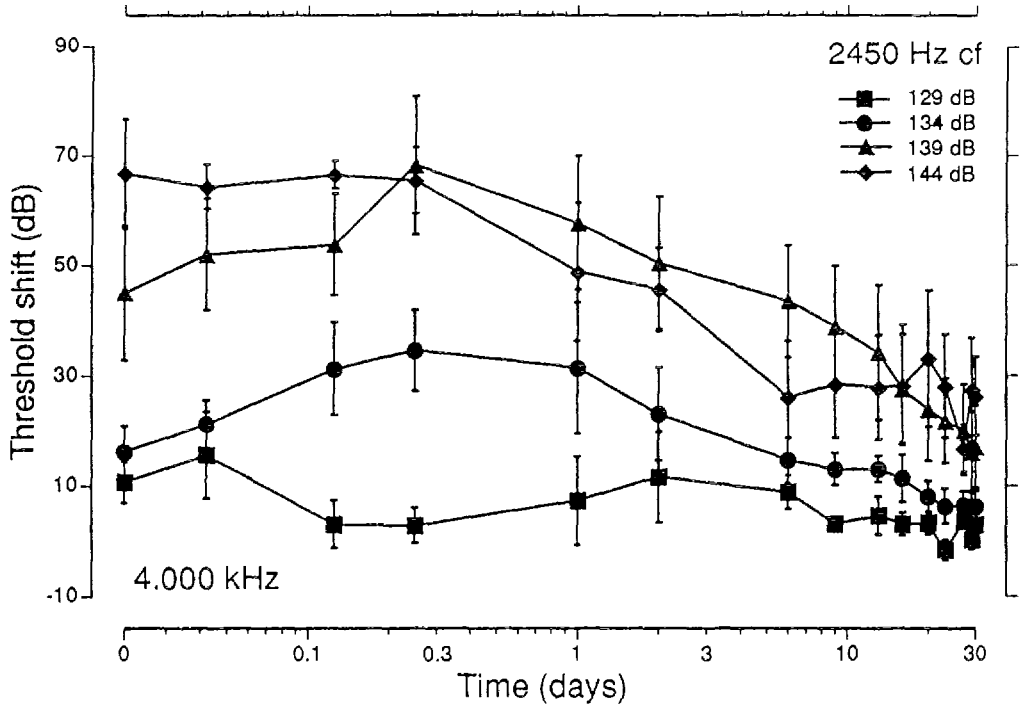

Figure 54. The mean threshold recovery curves for the groups exposed to the 2.450 kHz CF impulse at the indicated peak SPL for the 4.000 kHz audiometric test frequency.

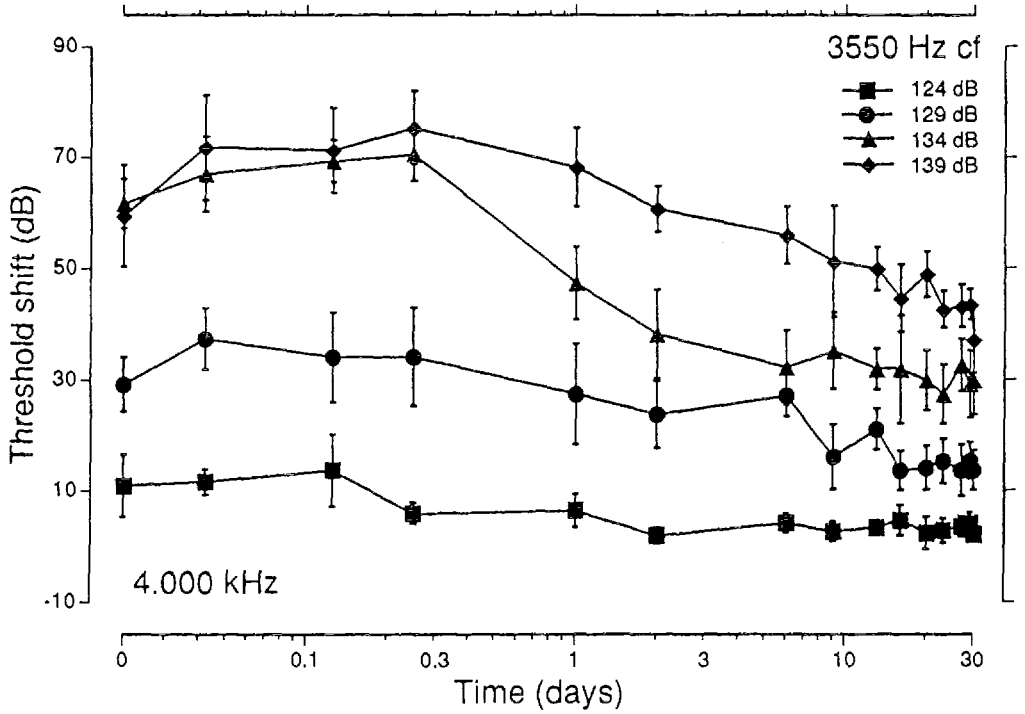

Figure 55. The mean threshold recovery curves for the groups exposed to the 3.550 kHz CF impulse at the indicated peak SPL for the 4.000 kHz audiometric test frequency.

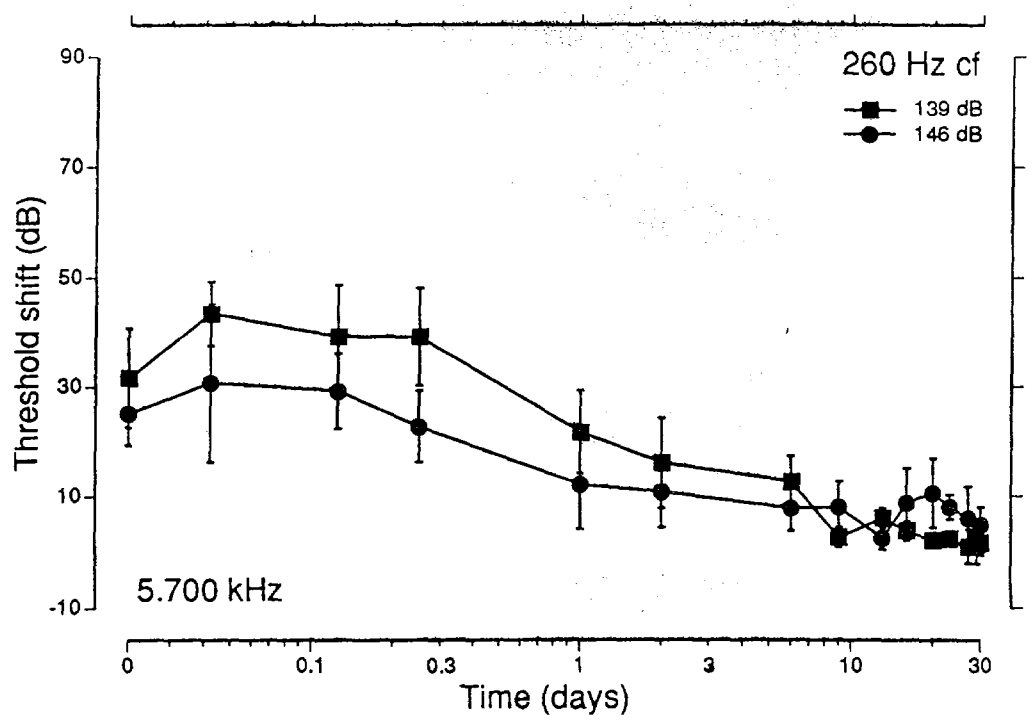

Figure 56. The mean threshold recovery curves for the groups exposed to the 0.260 kHz CF impulse at the indicated peak SPL for the 5.700 kHz audiometric test frequency.

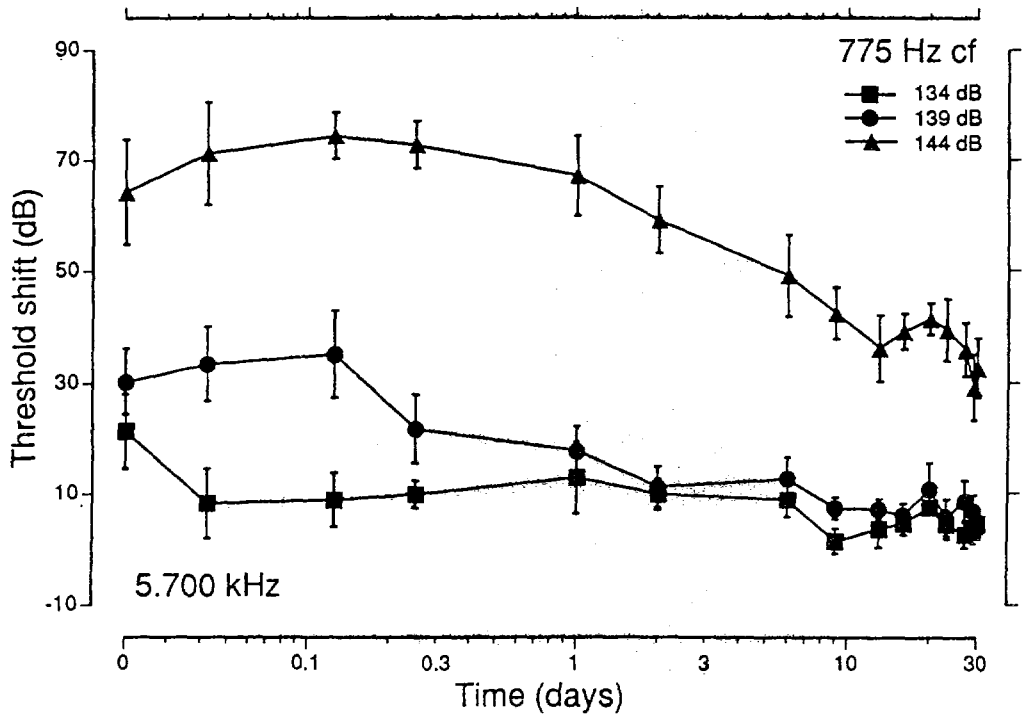

Figure 57. The mean threshold recovery curves for the groups exposed to the 0.775 kHz CF impulse at the indicated peak SPL for the 5.700 kHz audiometric test frequency.

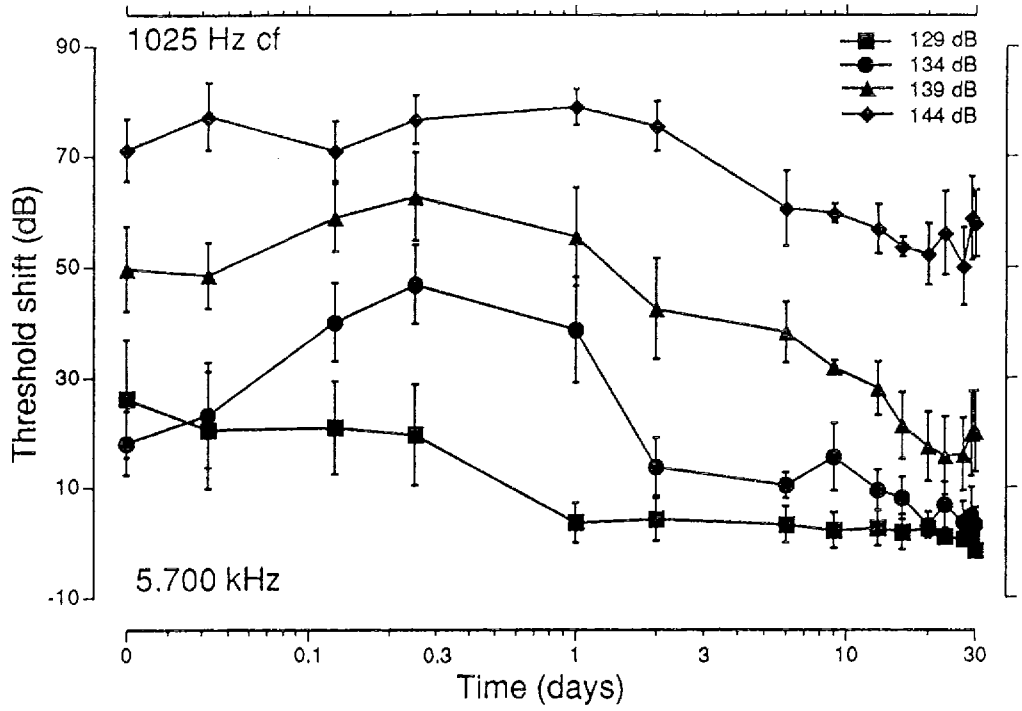

Figure 58. The mean threshold recovery curves for the groups exposed to the 1.025 kHz CF impulse at the indicated peak SPL for the 5.700 kHz audiometric test frequency.

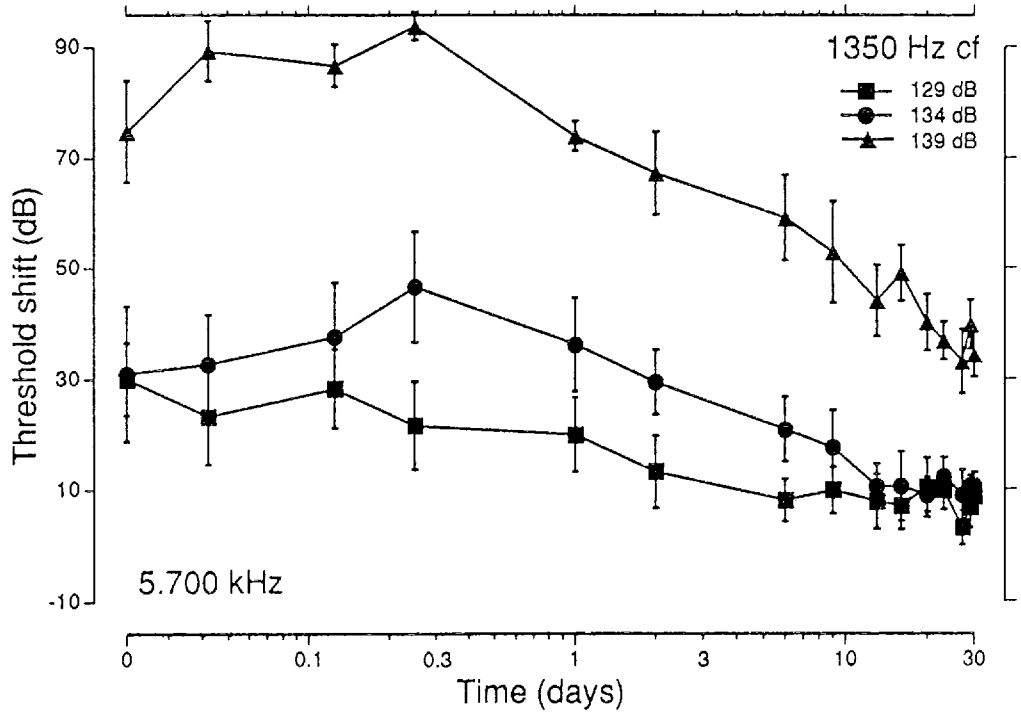

Figure 59. The mean threshold recovery curves for the groups exposed to the 1.350 kHz CF impulse at the indicated peak SPL for the 5.700 kHz audiometric test frequency.

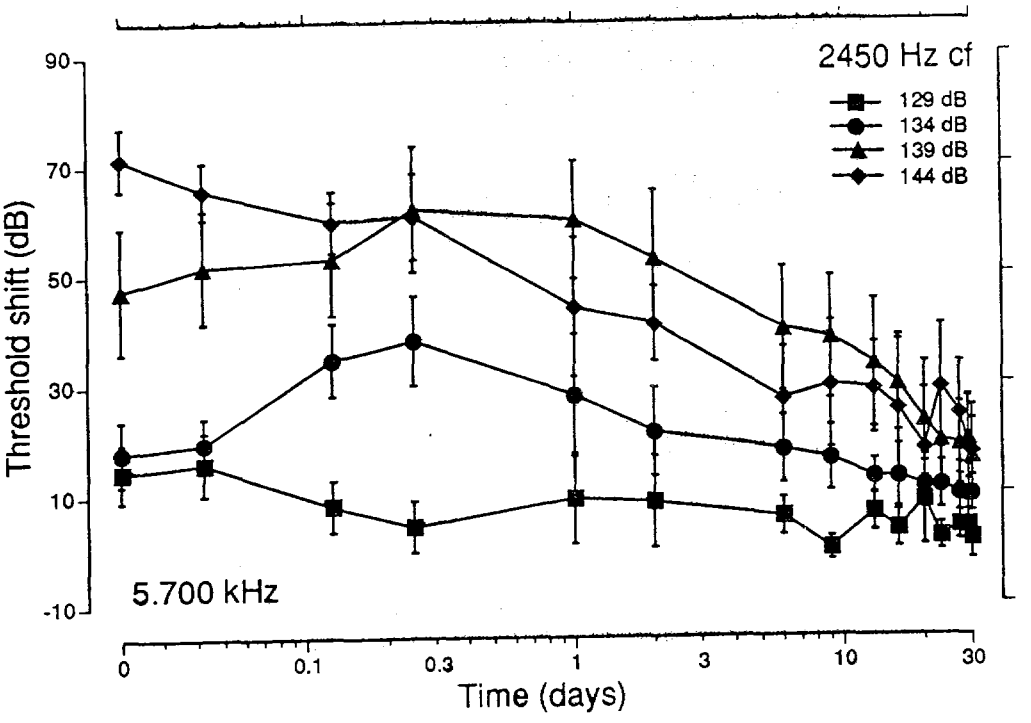

Figure 60. The mean threshold recovery curves for the groups exposed to the 2.450 kHz CF impulse at the indicated peak SPL for the 5.700 kHz audiometric test frequency.

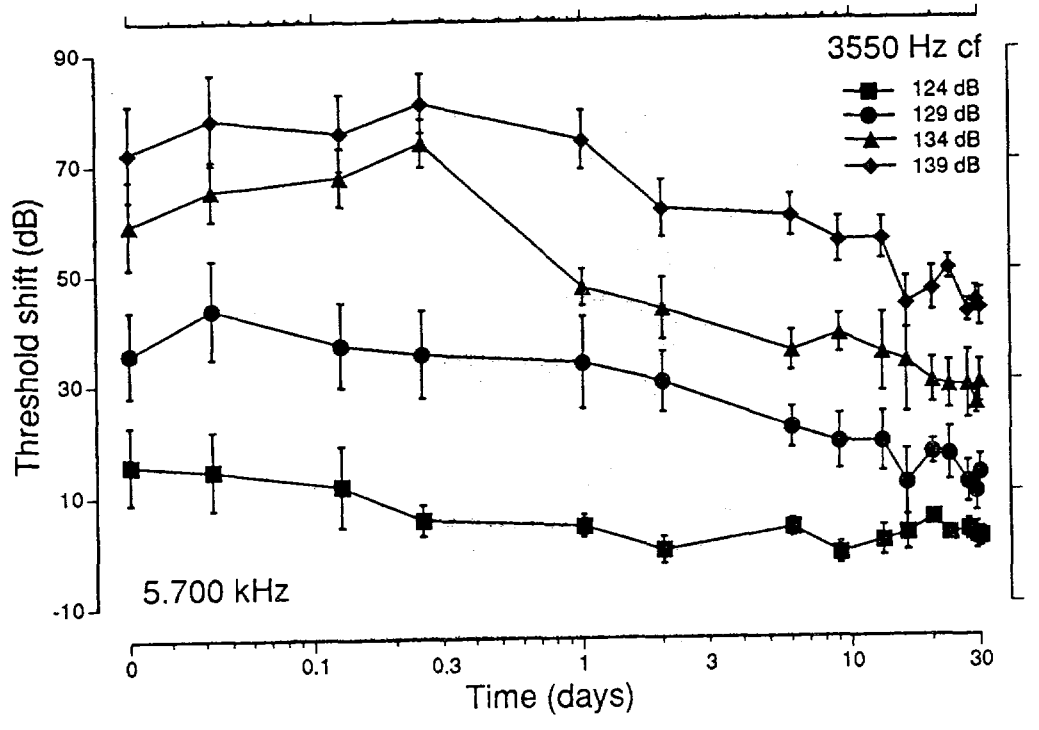

Figure 61. The mean threshold recovery curves for the groups exposed to the 3.550 kHz CF impulse at the indicated peak SPL for the 5.700 kHz audiometric test frequency.

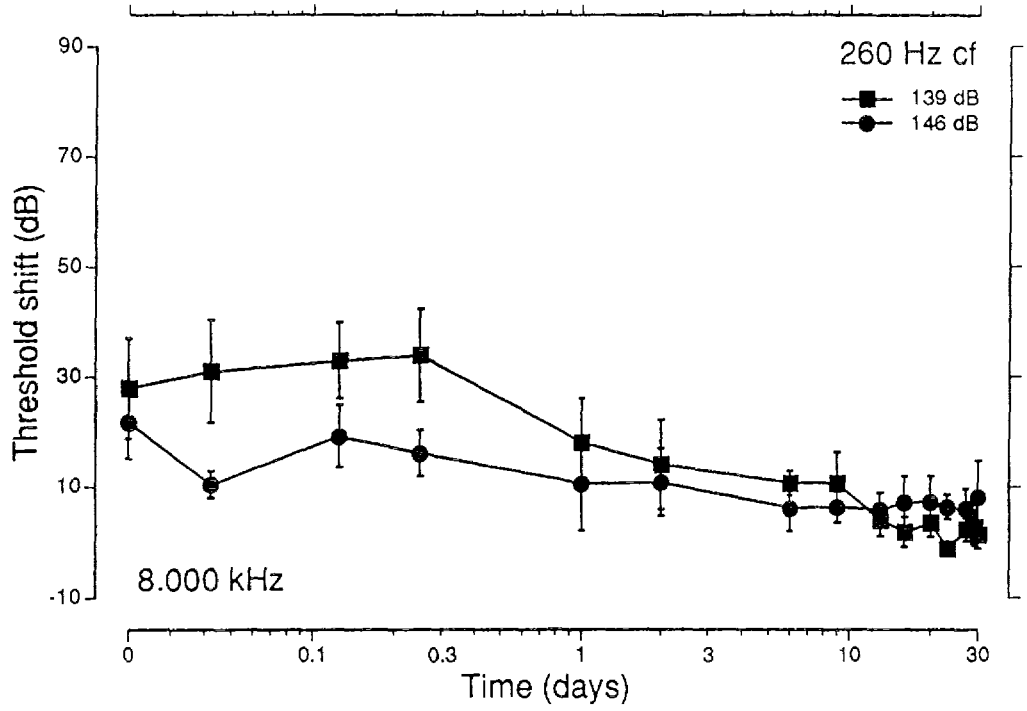

Figure 62. The mean threshold recovery curves for the groups exposed to the 0.260 kHz CF impulse at the indicated peak SPL for the 8.000 kHz audiometric test frequency.

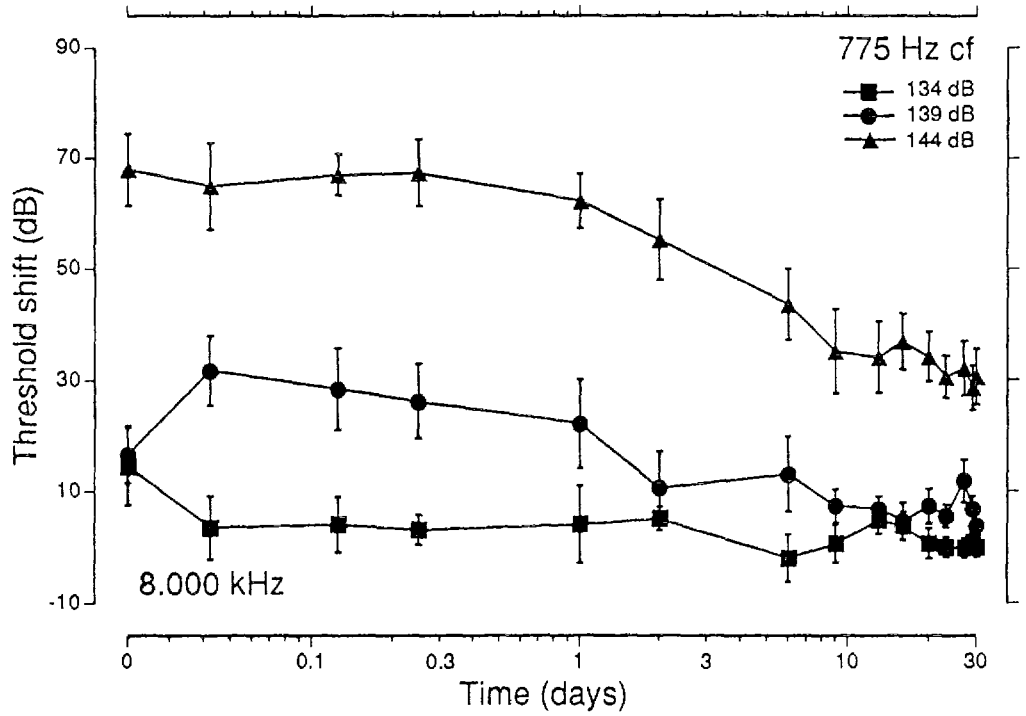

Figure 63. The mean threshold recovery curves for the groups exposed to the 0.775 kHz CF impulse at the indicated peak SPL for the 8.000 kHz audiometric test frequency.

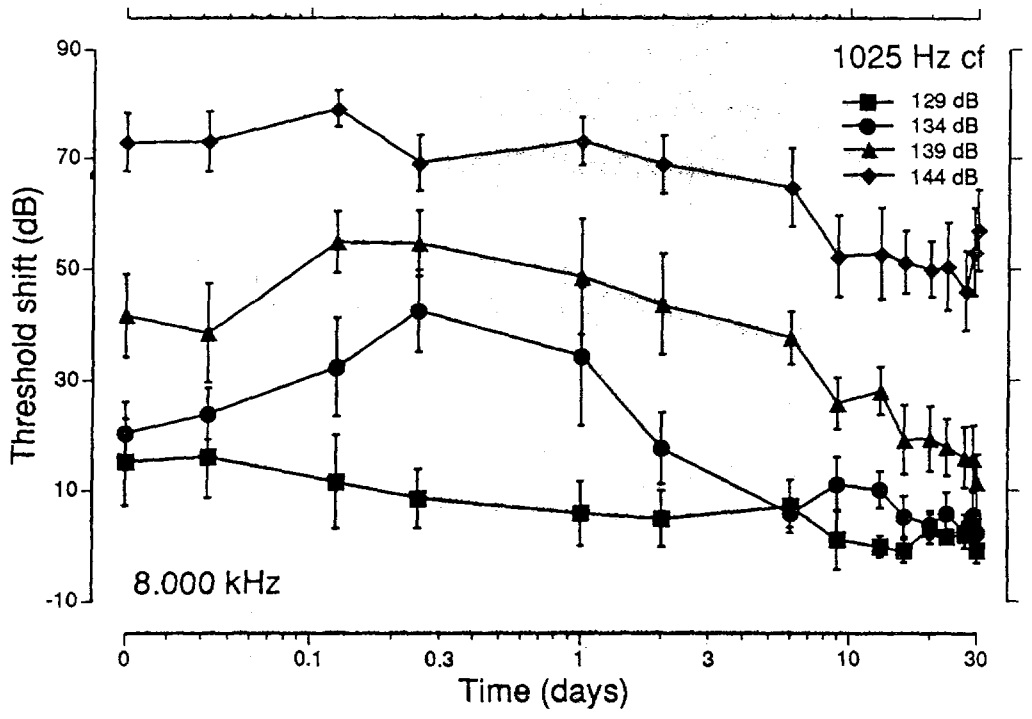

Figure 64. The mean threshold recovery curves for the groups exposed to the 1.025 kHz CF impulse at the indicated peak SPL for the 8.000 kHz audiometric test frequency.

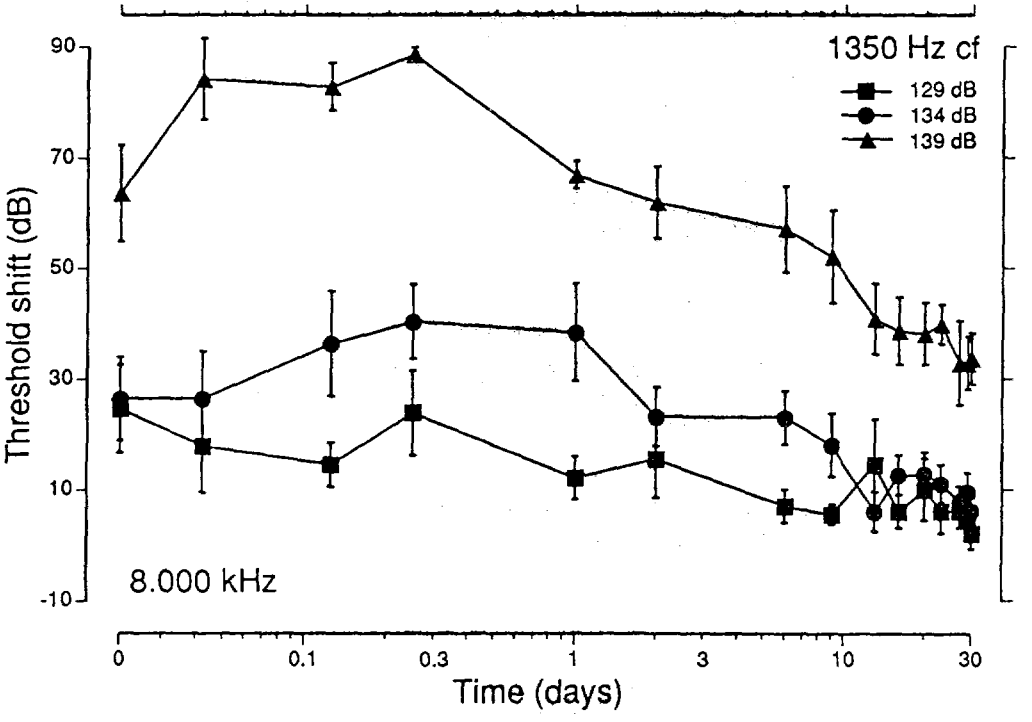

Figure 65. The mean threshold recovery curves for the groups exposed to the 1.350 kHz CF impulse at the indicated peak SPL for the 8.000 kHz audiometric test frequency.

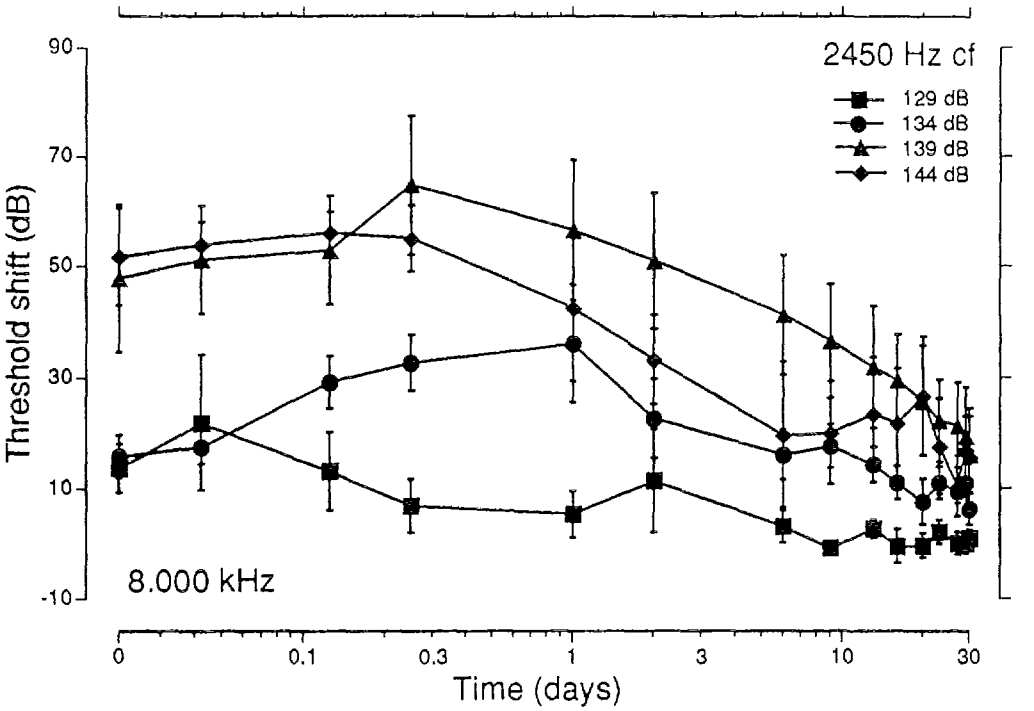

Figure 66. The mean threshold recovery curves for the groups exposed to the 2.450 kHz CF impulse at the indicated peak SPL for the 8.000 kHz audiometric test frequency.

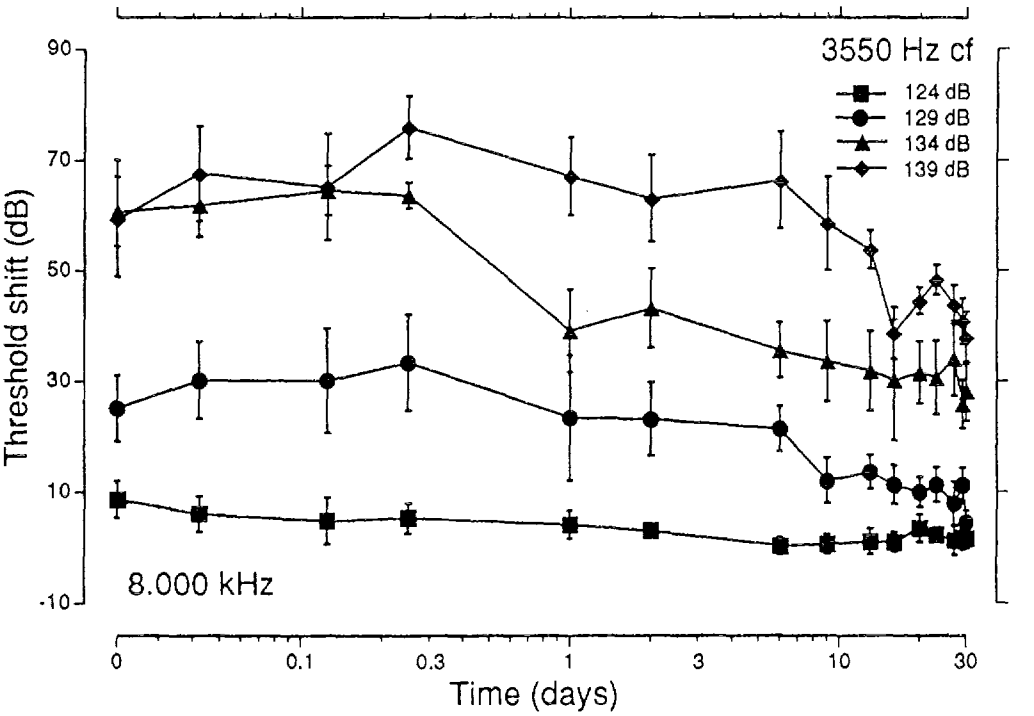

Figure 67. The mean threshold recovery curves for the groups exposed to the 3.550 kHz CF impulse at the indicated peak SPL for the 8.000 kHz audiometric test frequency.

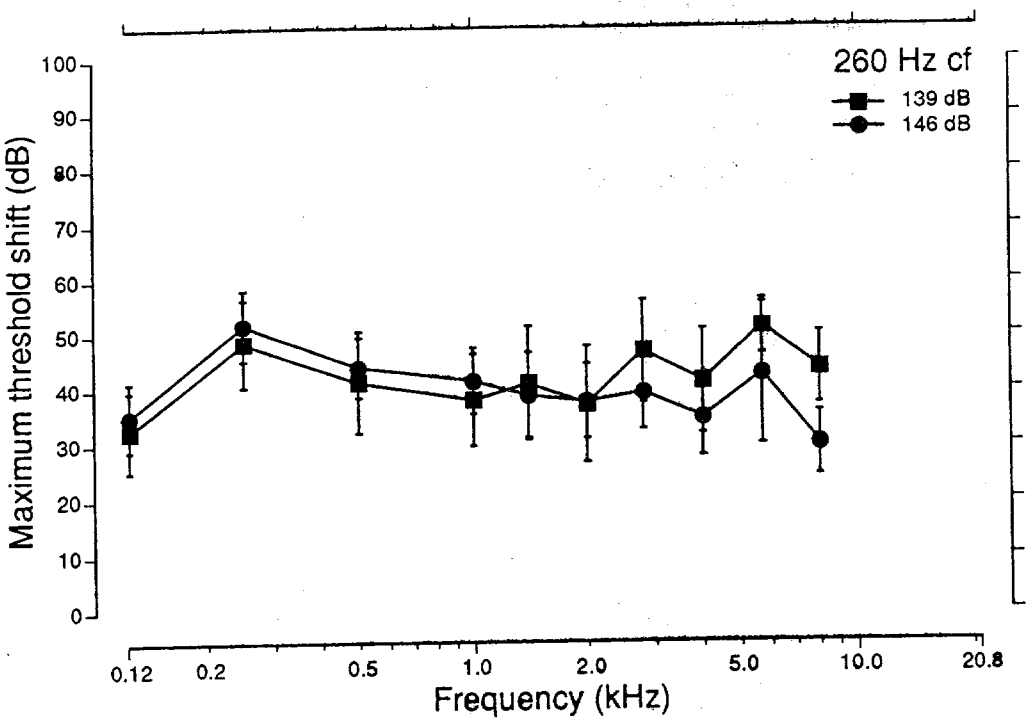

Figure 68. The group mean maximum threshold shift for each audiometric test frequency following exposure to the 0.260 kHz CF impulse at the indicated peak SPL.

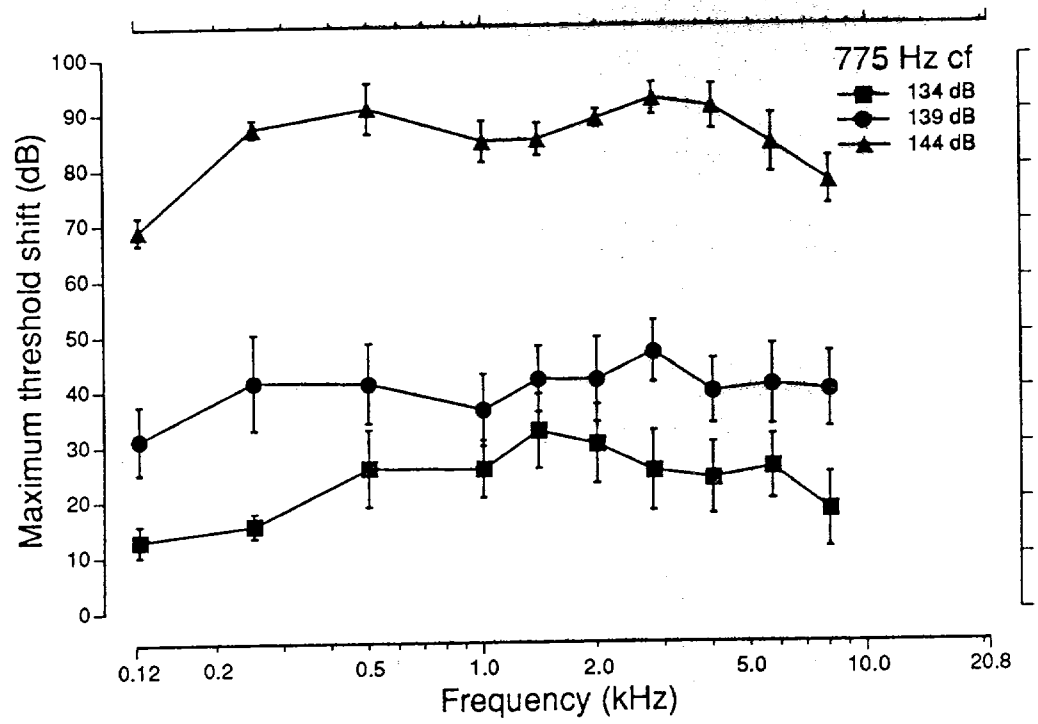

Figure 69. The group mean maximum threshold shift for each audiometric test frequency following exposure to the 0.775 kHz CF impulse at the indicated peak SPL.

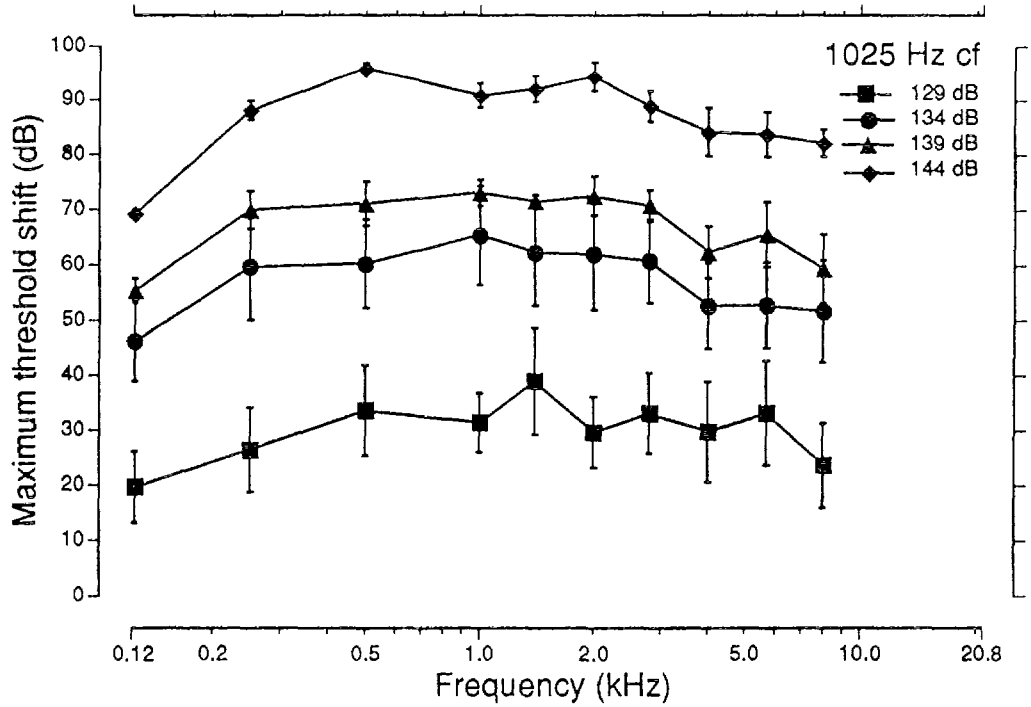

Figure 70. The group mean maximum threshold shift for each audiometric test frequency following exposure to the 1.025 kHz CF impulse at the indicated peak SPL.

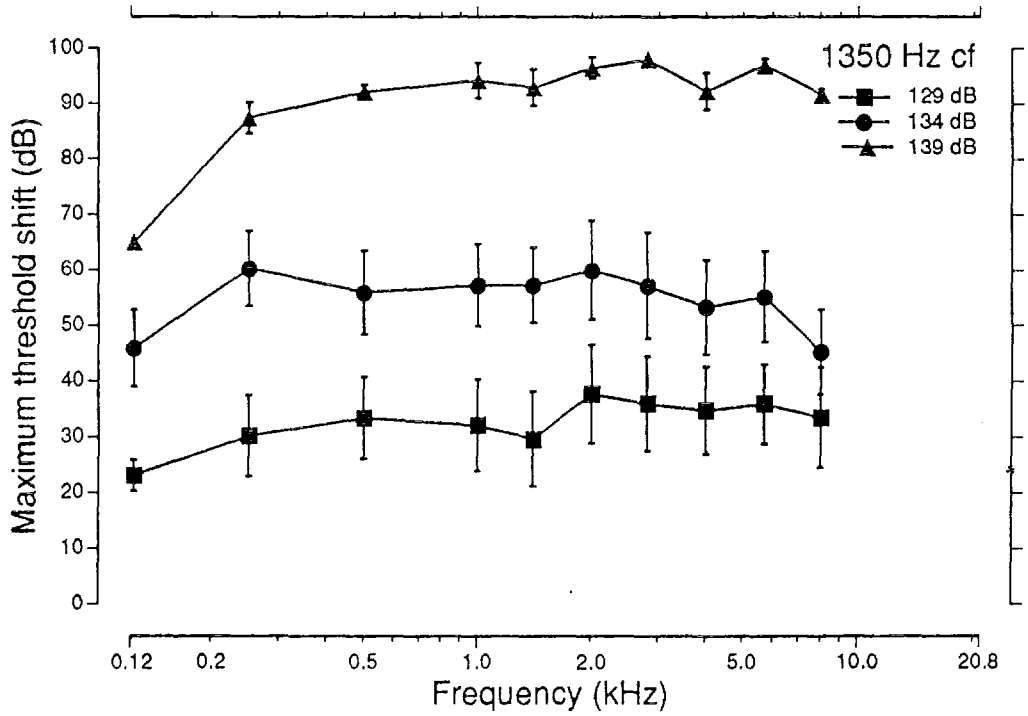

Figure 71. The group mean maximum threshold shift for each audiometric test frequency following exposure to the 1.350 kHz CF impulse at the indicated peak SPL.

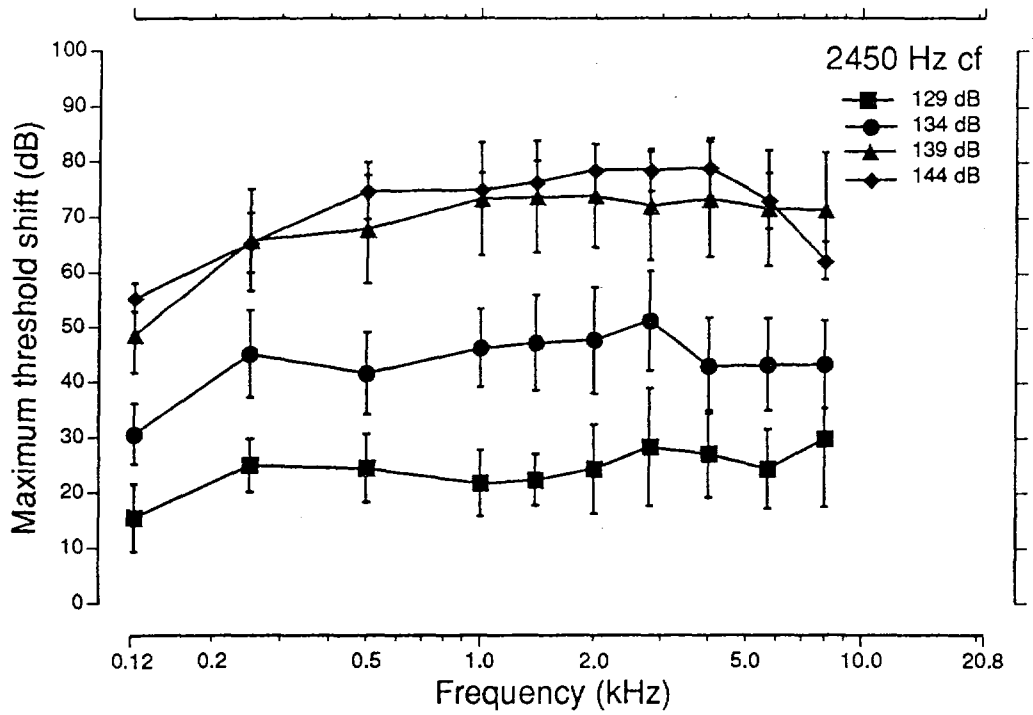

Figure 72. The group mean maximum threshold shift for each audiometric test frequency following exposure to the 2.450 kHz CF impulse at the indicated peak SPL.

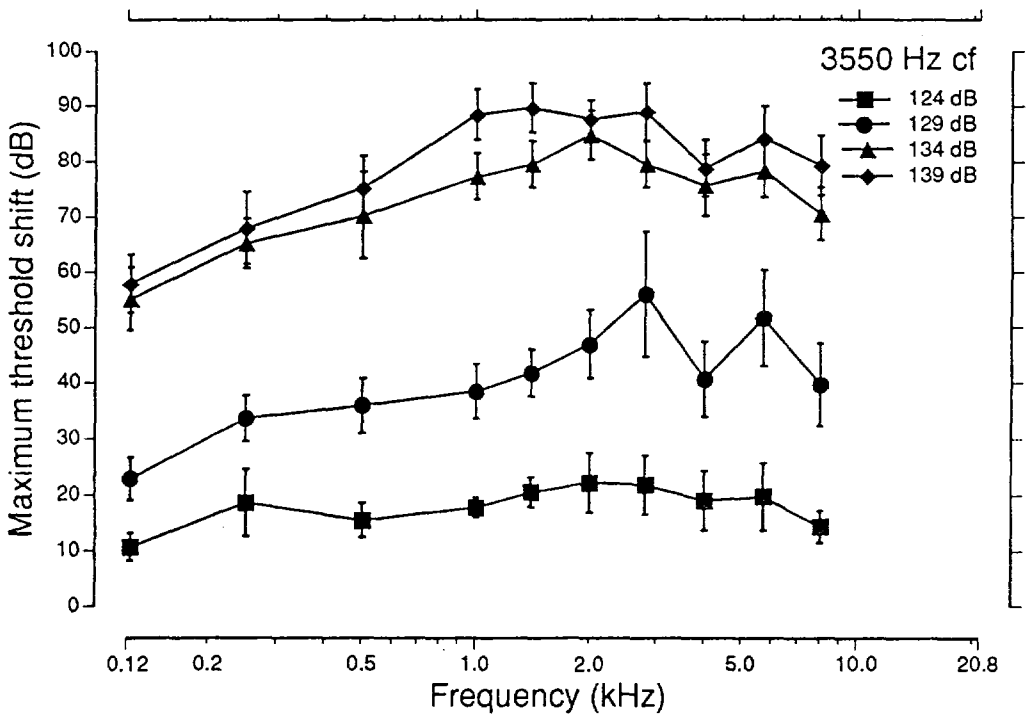

Figure 73. The group mean maximum threshold shift for each audiometric test frequency following exposure to the 3.550 kHz CF impulse at the indicated peak SPL.

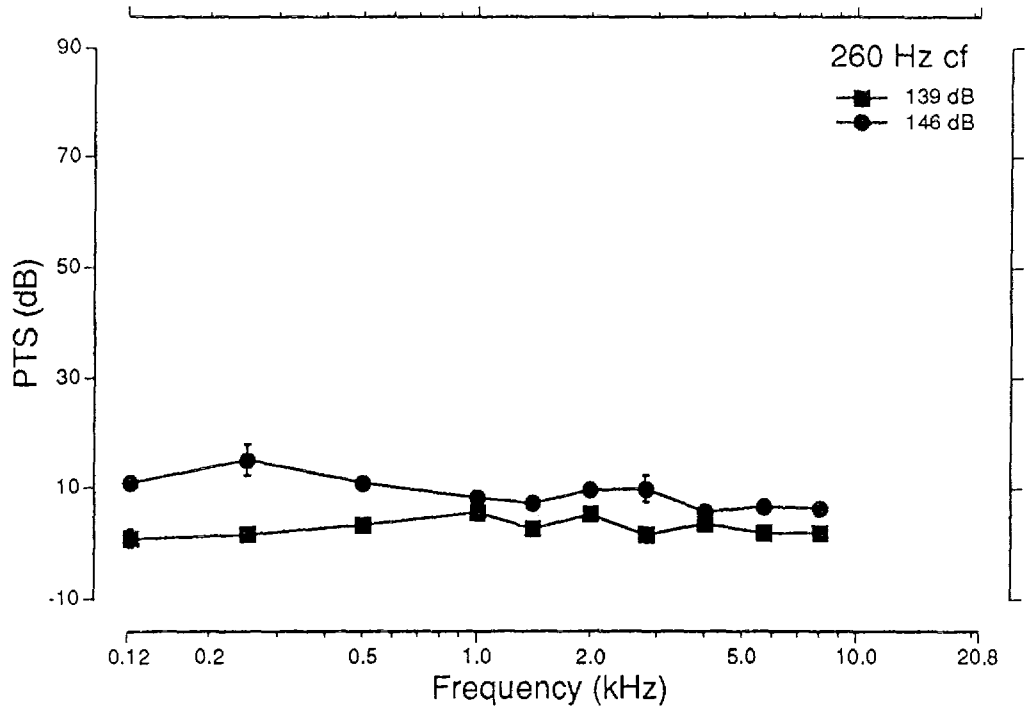

Figure 74. The group mean permanent threshold shift (PTS) for each audiometric test frequency following exposure to the 0.260 kHz CF impulse at the indicated peak SPL.

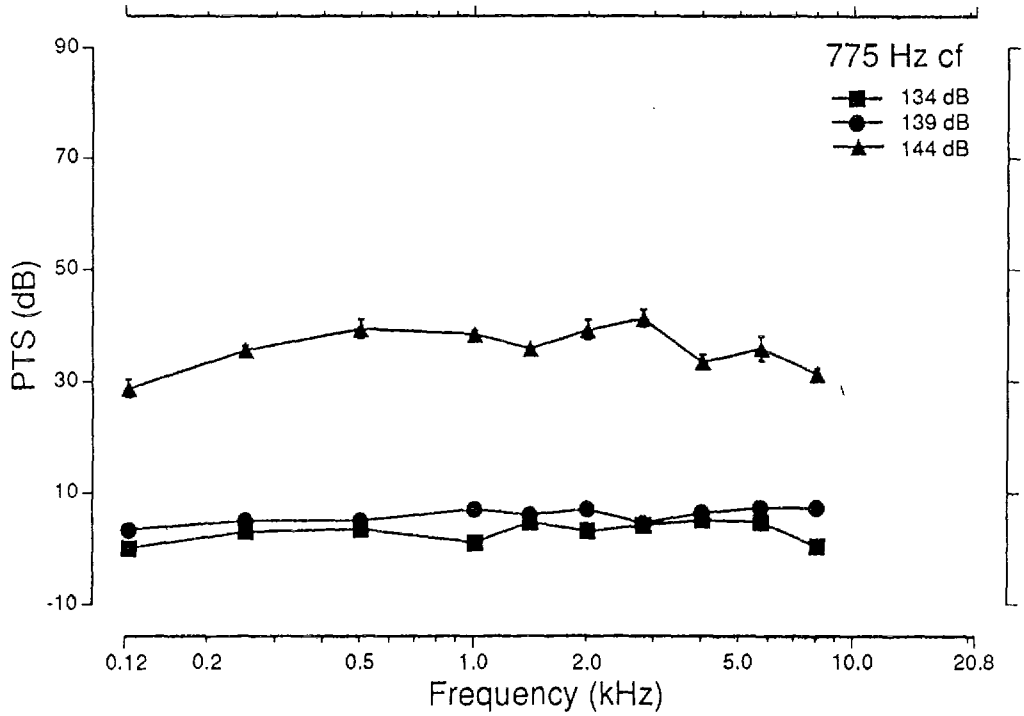

Figure 75. The group mean permanent threshold shift (PTS) for each audiometric test frequency following exposure to the 0.775 kHz CF impulse at the indicated peak SPL.

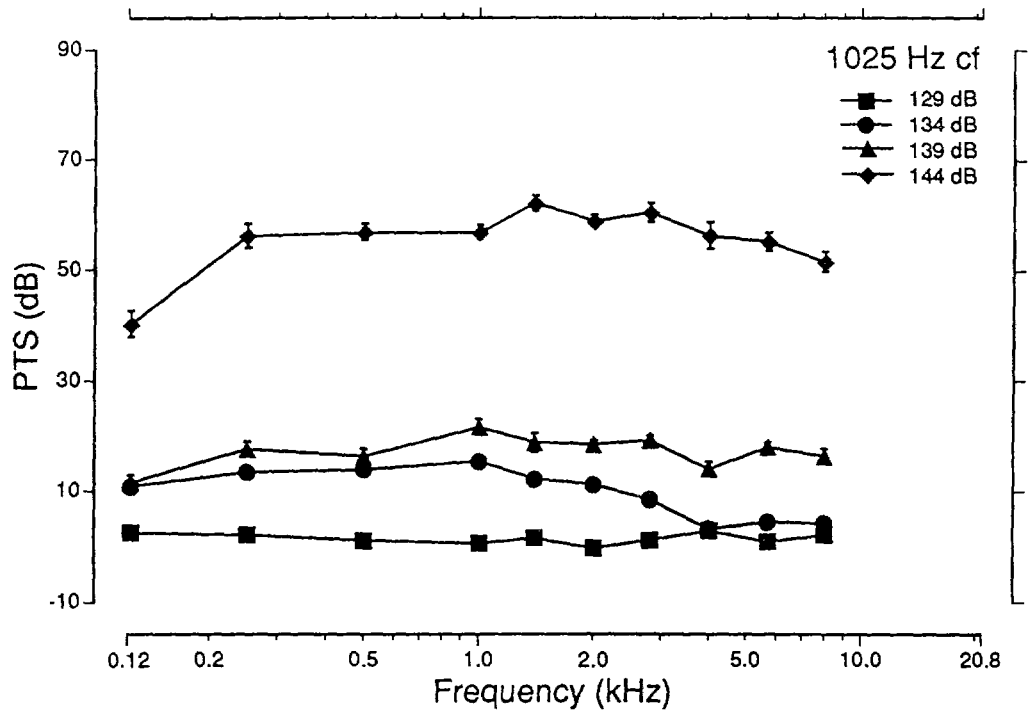

Figure 76. The group mean permanent threshold shift (PTS) for each audiometric test frequency following exposure to the 1.025 kHz CF impulse at the indicated peak SPL.

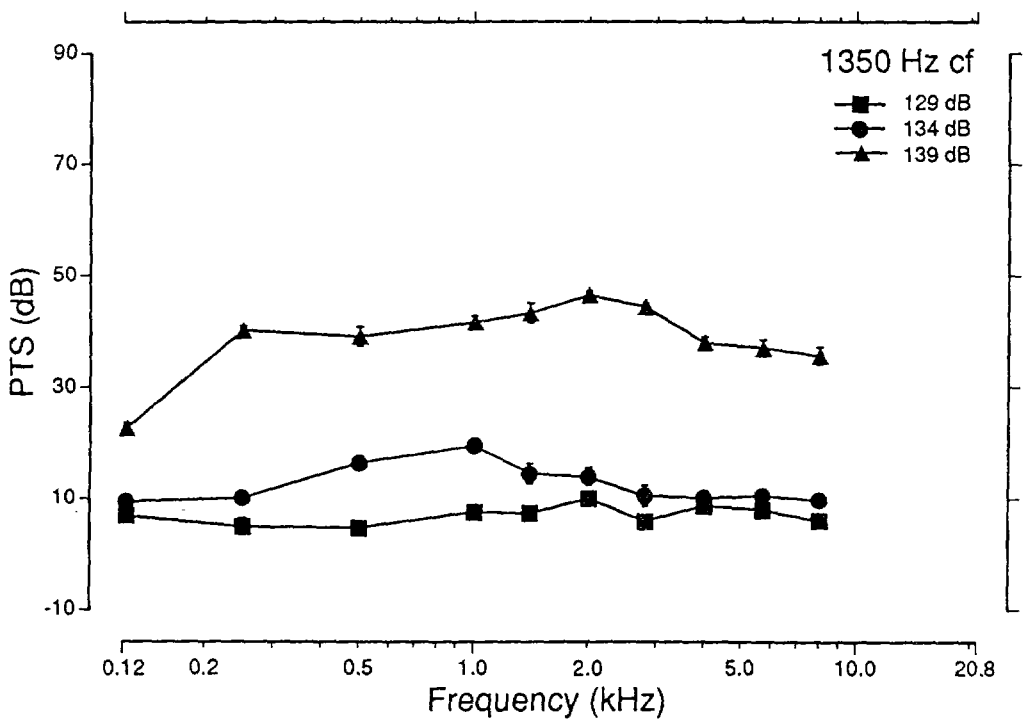

Figure 77. The group mean permanent threshold shift (PTS) for each audiometric test frequency following exposure to the 1.350 kHz CF impulse at the indicated peak SPL.

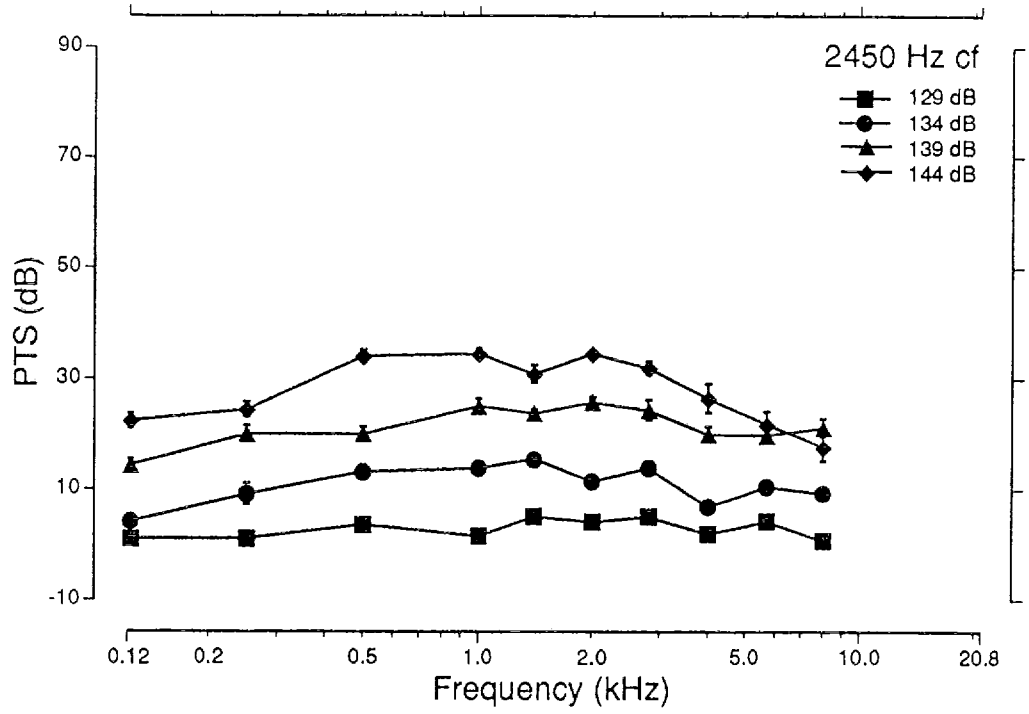

Figure 78. The group mean permanent threshold shift (PTS) for each audiometric test frequency following exposure to the 2.450 kHz CF impulse at the indicated peak SPL.

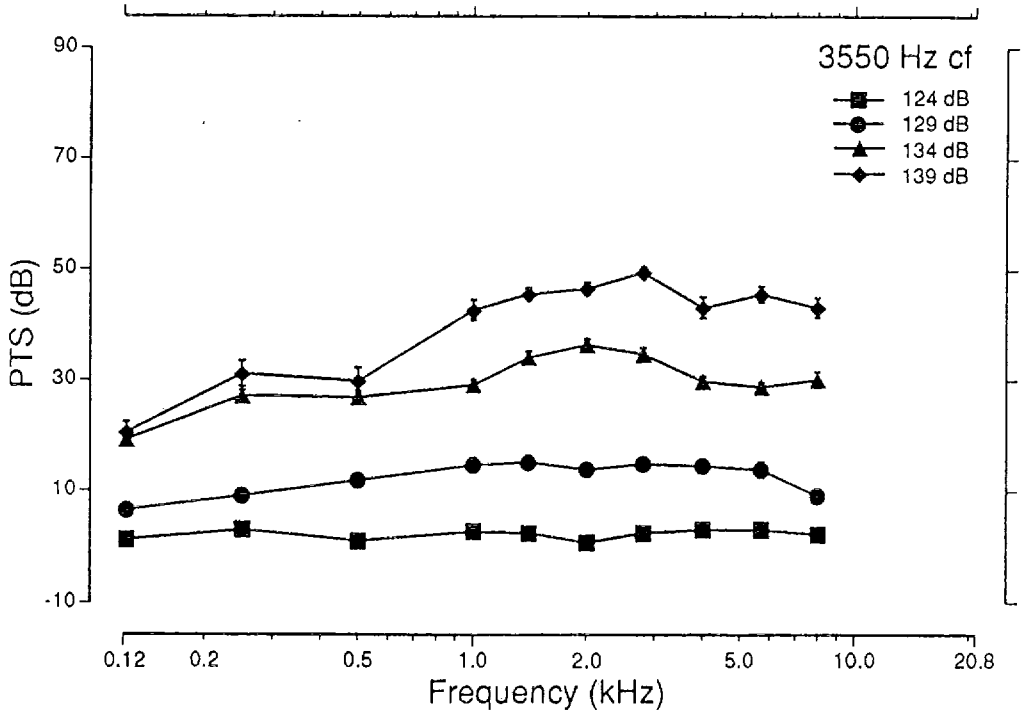

Figure 79. The group mean permanent threshold shift (PTS) for each audiometric test frequency following exposure to the 3.550 kHz CF impulse at the indicated peak SPL.

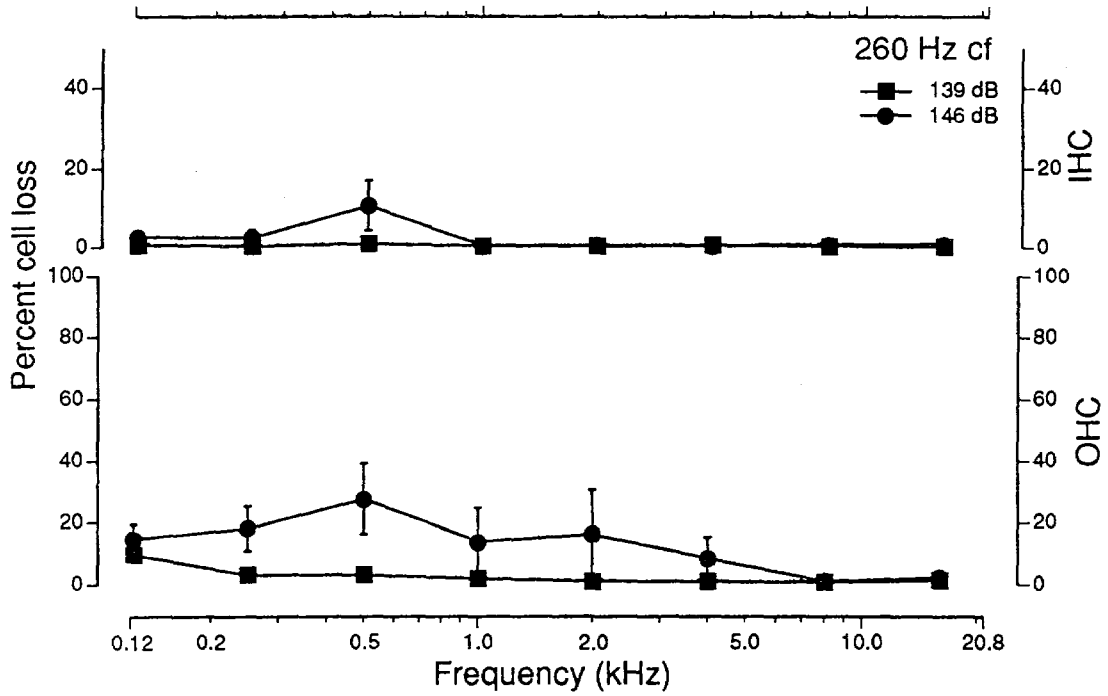

Figure 80. The group mean outer hair cell (OHC) loss and inner hair cell (IHC) loss within octave band lengths of the basilar membrane at the indicated frequencies following exposure to the 0.260 kHz CF impulse at the indicated peak SPL.

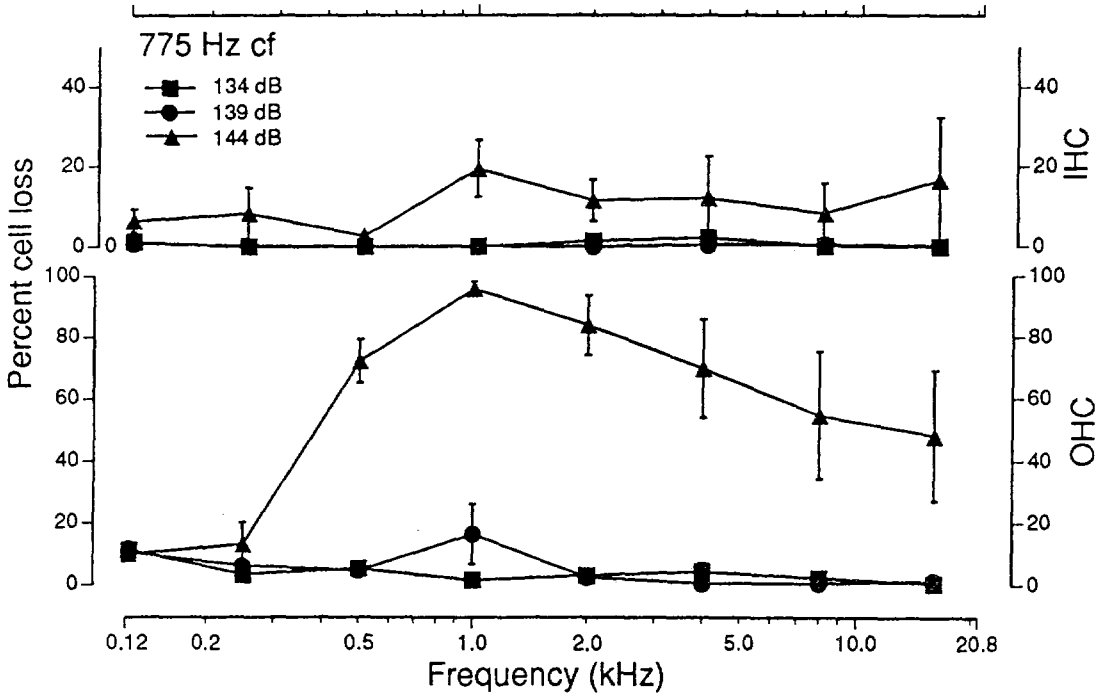

Figure 81. The group mean outer hair cell (OHC) loss and inner hair cell (IHC) loss within octave band lengths of the basilar membrane at the indicated frequencies following exposure to the 0.775 kHz CF impulse at the indicated peak SPL.

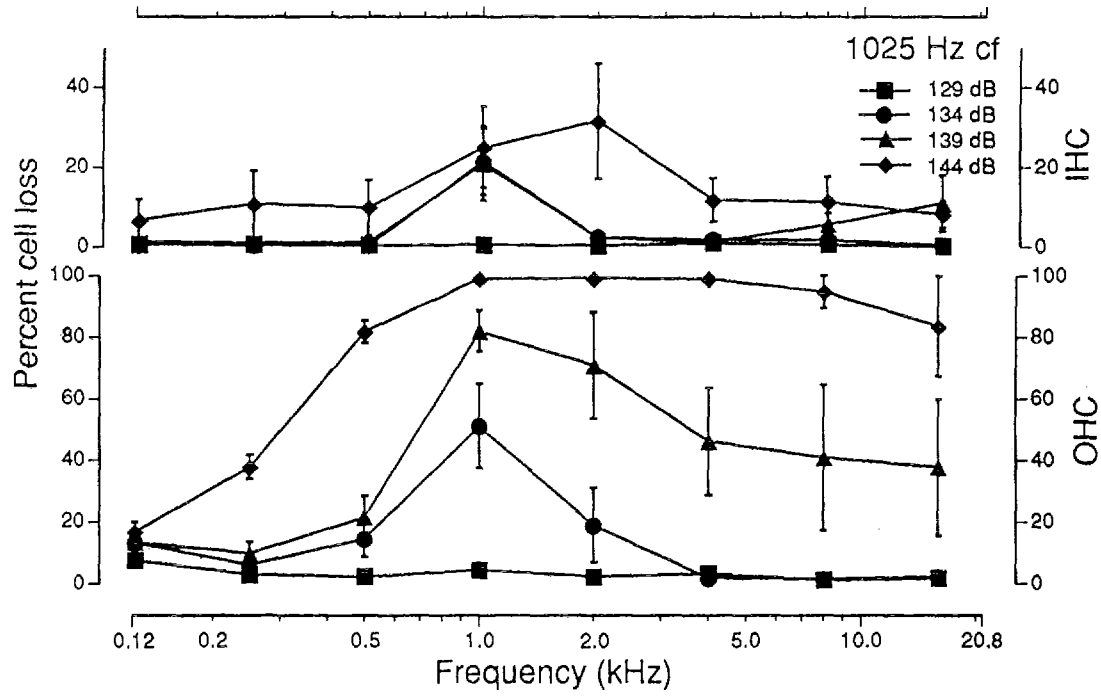

Figure 82. The group mean outer hair cell (OHC) loss and inner hair cell (IHC) loss within octave band lengths of the basilar membrane at the indicated frequencies following exposure to the 1.025 kHz CF impulse at the indicated peak SPL.

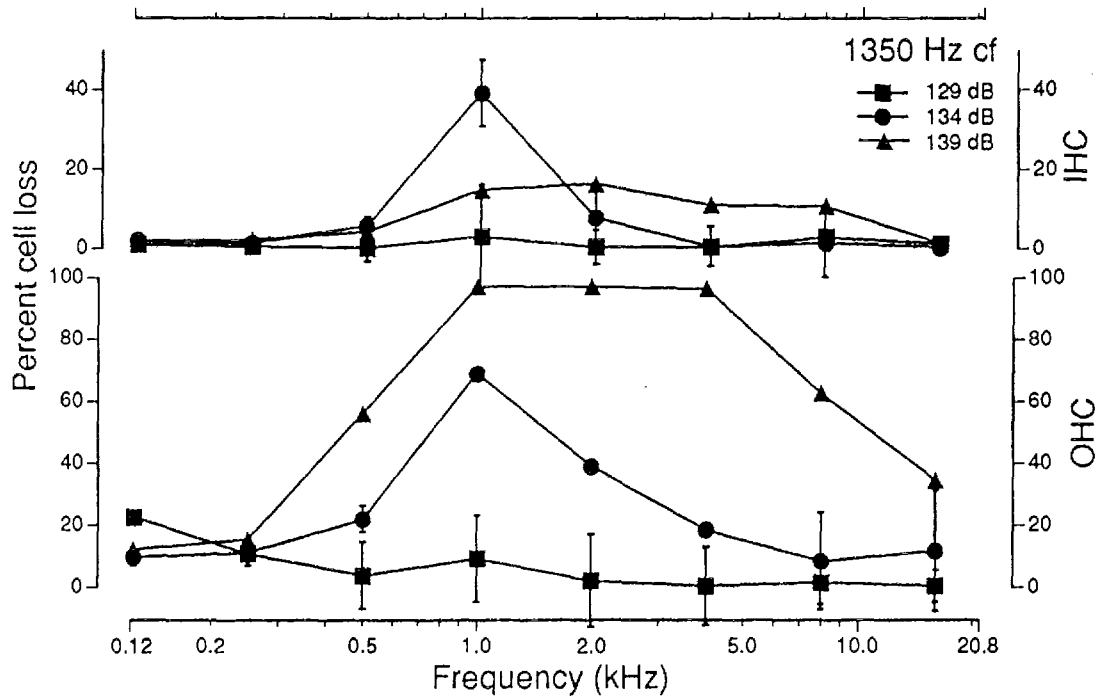

Figure 83. The group mean outer hair cell (OHC) loss and inner hair cell (IHC) loss within octave band lengths of the basilar membrane at the indicated frequencies following exposure to the 1.350 kHz CF impulse at the indicated peak SPL.

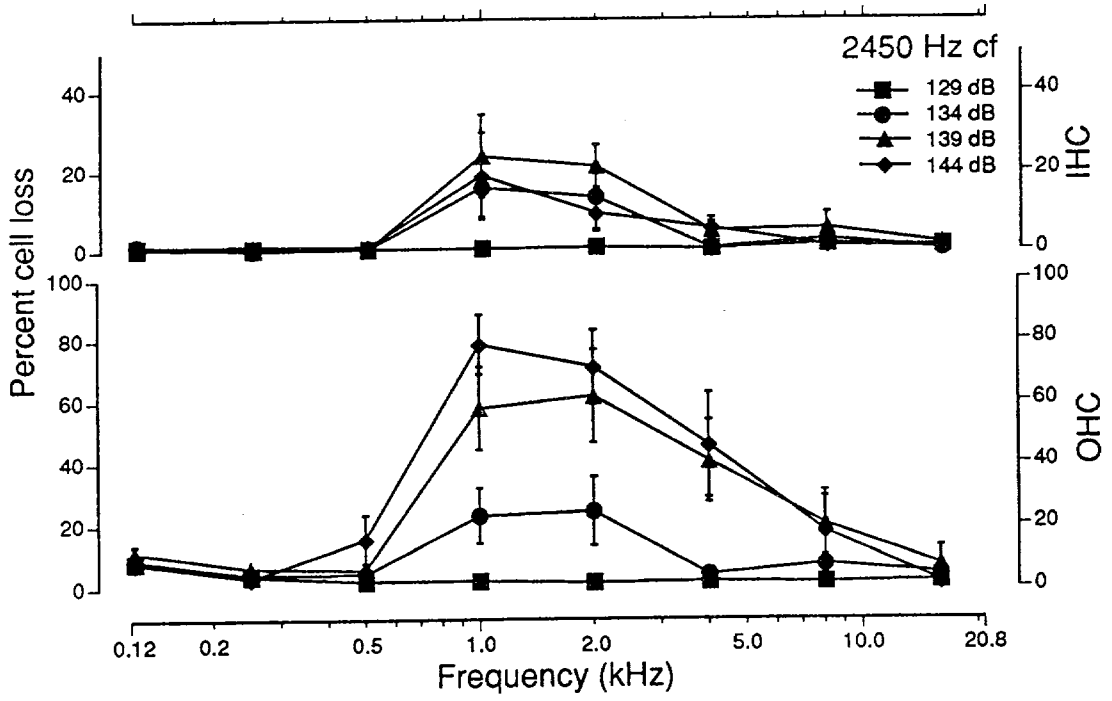

Figure 84. The group mean outer hair cell (OHC) loss and inner hair cell (IHC) loss within octave band lengths of the basilar membrane at the indicated frequencies following exposure to the 2.450 kHz CF impulse at the indicated peak SPL.

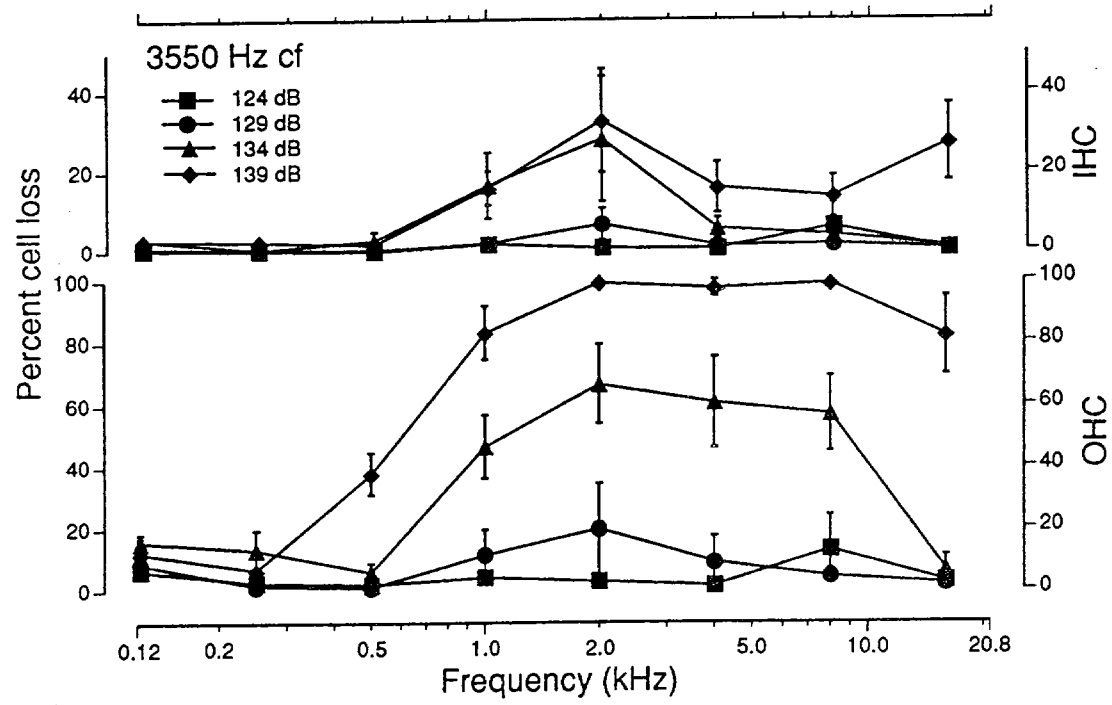

Figure 85. The group mean outer hair cell (OHC) loss and inner hair cell (IHC) loss within octave band lengths of the basilar membrane at the indicated frequencies following exposure to the 3.550 kHz CF impulse at the indicated peak SPL.

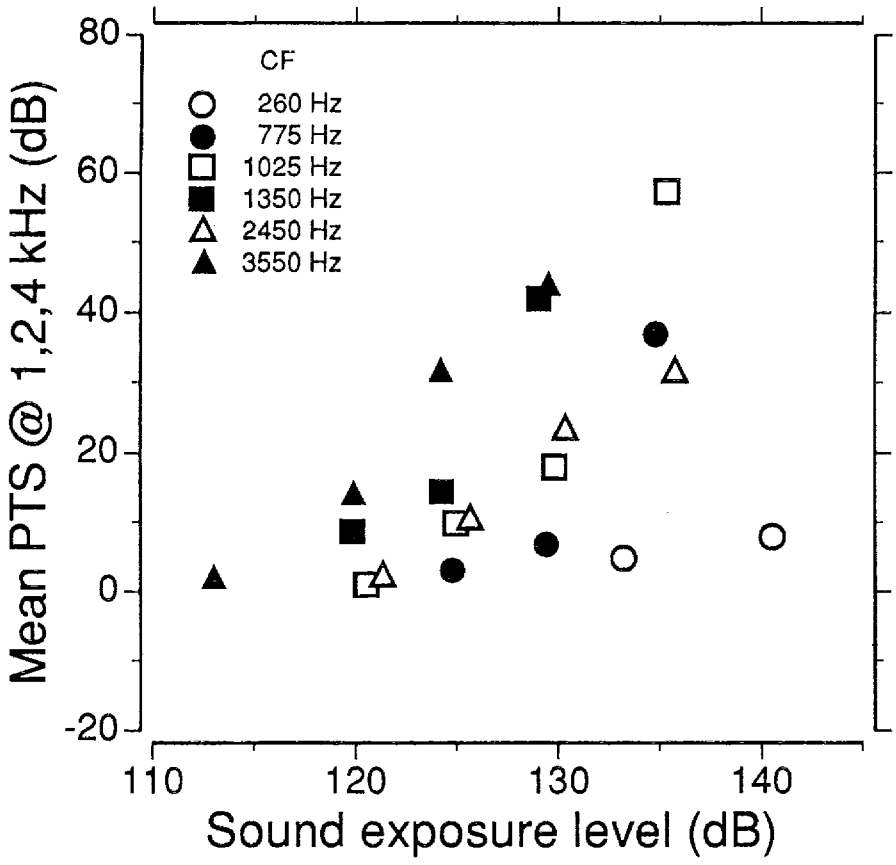

Figure 86. The group mean PTS evaluated at 1, 2 and 4 kHZ ($\overline{PTS}_{1,2,4}$) as a function of the total sound exposure level for the twenty groups of animals exposed to the narrow band impulses.

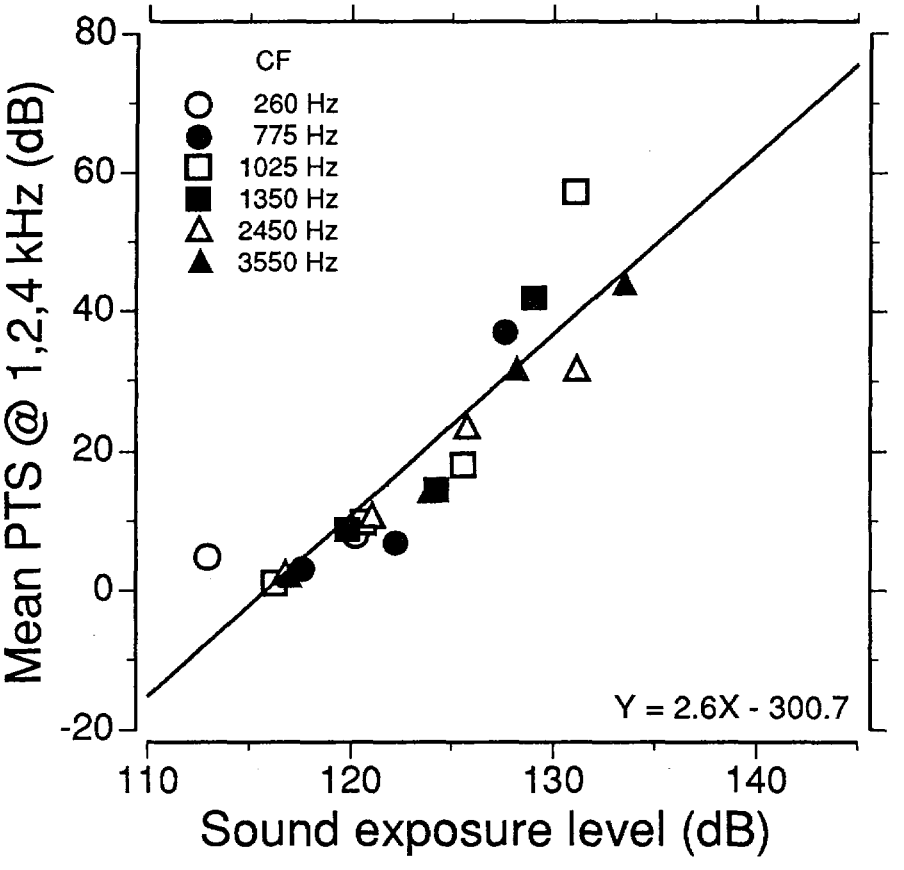

Figure 87. The $\overline{PTS}_{1,2,4}$ as a function of the P-weighted total sound exposure level. The regression line yields a correlation coefficient of 0.904.

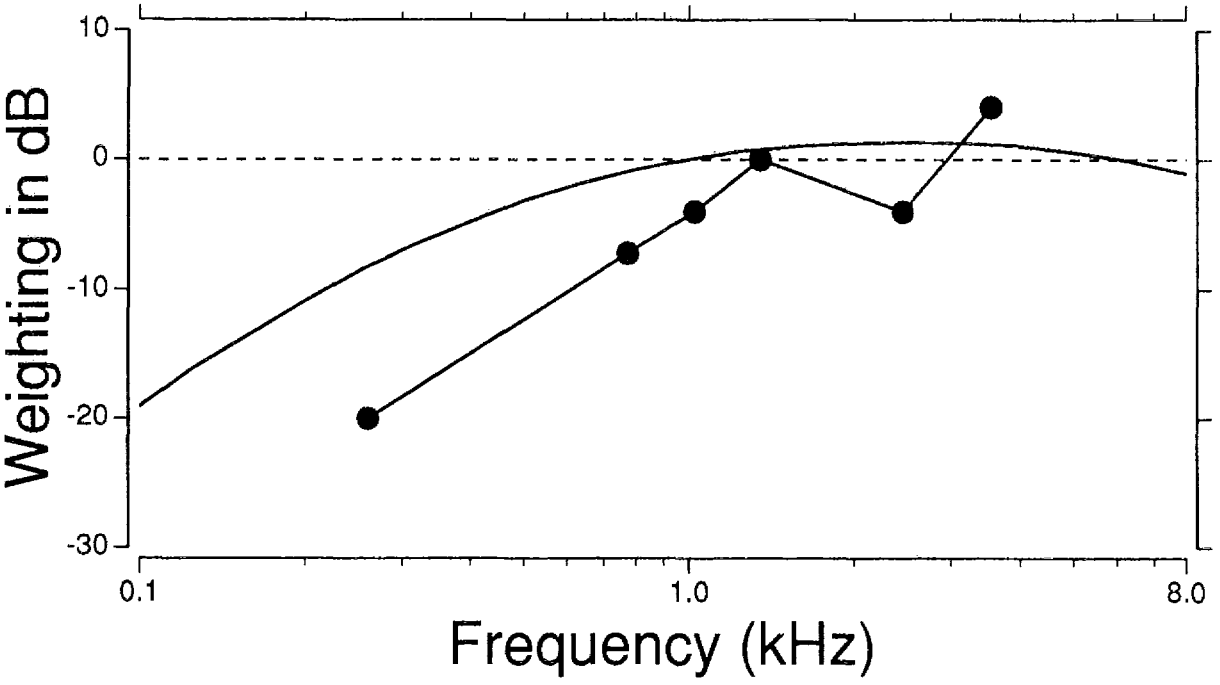

Figure 88. The empirical P-weighting function (symbols) derived from the narrow band exposure data along with the conventional A-weighting function (solid line).

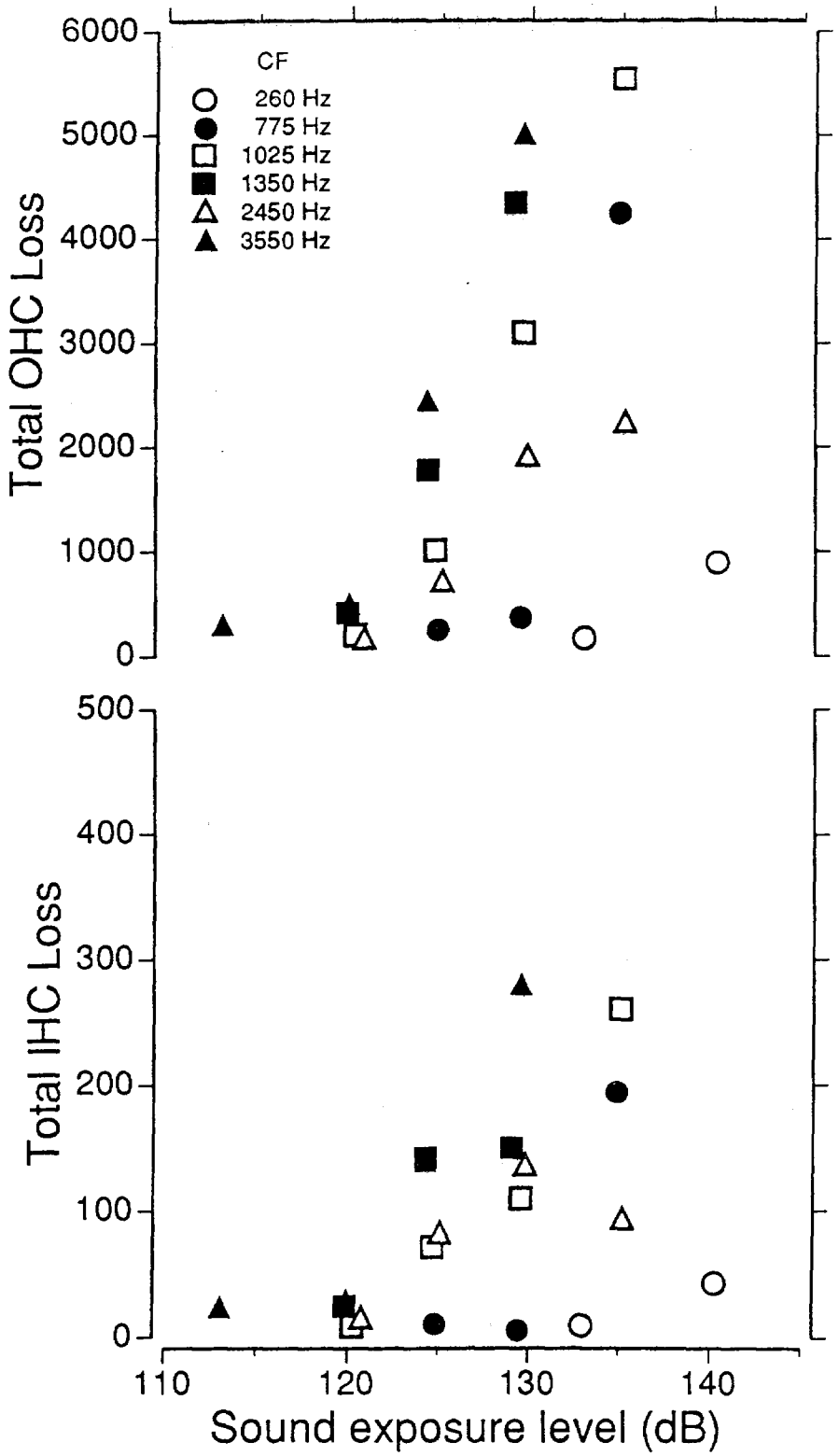

Figure 89. The group mean total outer (upper) and inner (lower) hair cell loss as a function of the total sound exposure level for the twenty groups of animals exposed to the narrow band impulses.

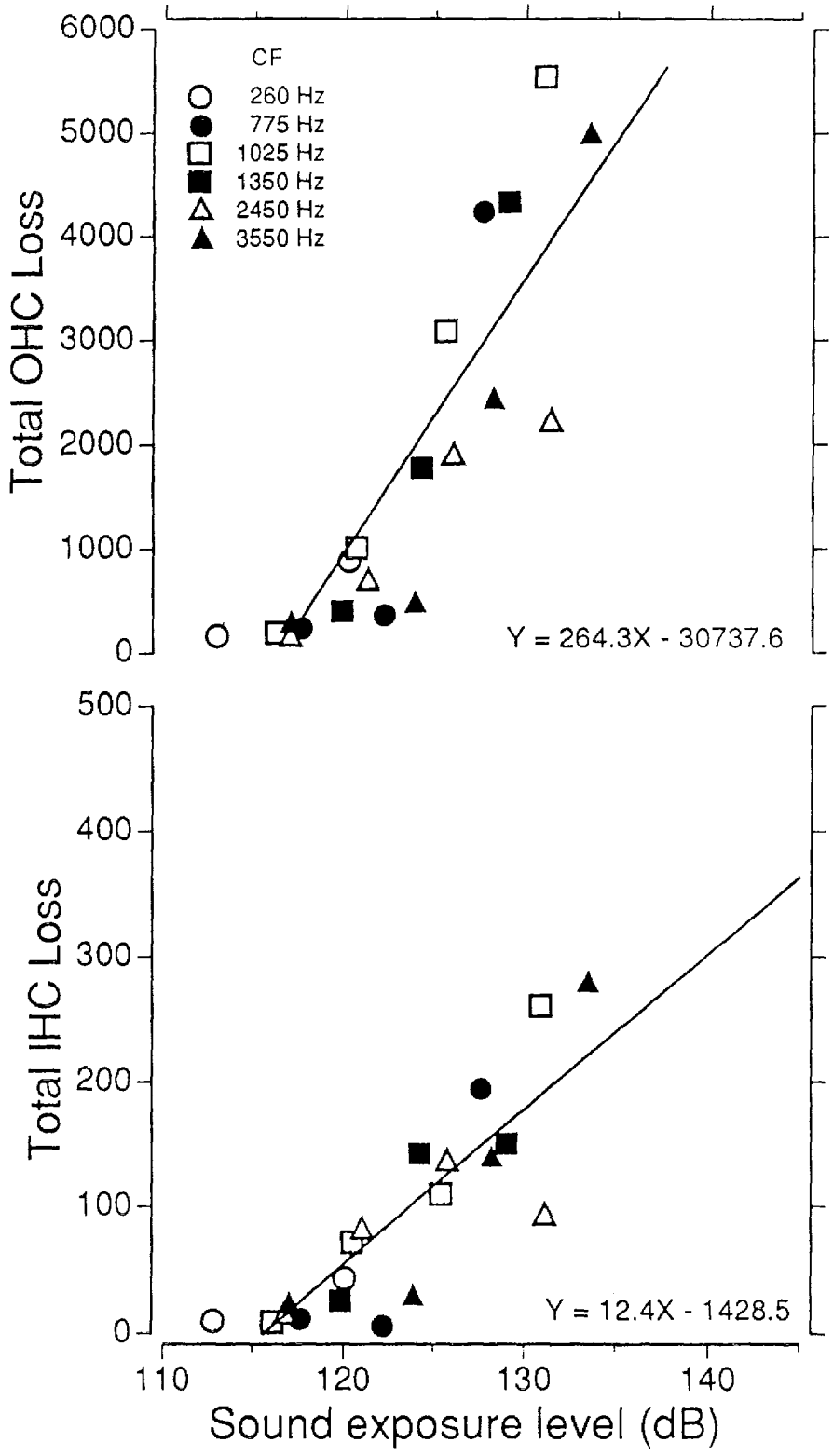

Figure 90. The group mean total outer (upper) and inner (lower) hair cell loss as a function of the P-weighted total sound level. The regression lines yield correlation coefficients of 0.858 and 0.849 for outer and inner hair cell loss respectively.

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Appendix A

List of manufacturers

Altec Lansing Corporation
1515 South Manchester Avenue
Anaheim, CA 92803

Digital Equipment Corporation
Maynard, MA 01754